The Association
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PRINCIPLES OF AUTOMATIC MOTOR CONTROL

(REVISED REPRINT)

By B. FELTBOWER, B.Sc. (Eng.), A.M.I.E.E.

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CONTENTS

REFERENCE LIST.

af Auxiliary Fuse.
AR Accelerating Relay.
AS Auto-Starter.
AT Auto-Transformer.

BCR Brake Control Relay.
BR Brake Resistance.
BC Brake Contactor.

C Contactor.
CD Condenser.
cf Control Circuit Fuse.
CR Control Relay.

DBC Dynamic Brake Contactor.
DR Discharge Resistance.

ED Eddy-Current Brake Coil.
er Economy Resistance.

FC Forward Contactor.
FR Field Relay.
FSC Final Starting Contactor.

GFC Generator Field Contactor.

HC High-Speed Contactor.
HCR High-Speed Control Relay.
htc Trip Coil for HC.

IS Isolator.

LC Low-Speed Contactor.
LCR Low-Speed Control Relay.
ltc Trip Coil for LC.
LS Limit Switch.

MB Main-and-Brake Contactor.
MC Master Controller.
MF Main Fuses.
MFC Motor Field Contactor.

OL Overload Relay.

p Permanent Resistance.
PC Plug Braking Contactor.
pf Pilot Lamp Fuses.
PL Pilot Lamp.
PR Protective Thermal Relay.
PRS Plugging Resistance.

R Shunt Field Regulator.
RC Reverse Contactor.
RE Heating Element.
RF Rectifier.
RFC Rotor Final Contactor.
RN Run Contactor.
RR Retard Relay.
RR_1, RR_2, etc. } Switches on Rotor Regulator.
RRS Rotor Resistance.
RSC Rotor Starting Contactor.
RT Rectifier Thermal Overload Relay.

SC Starting Contactor (D.C.)
SR Starting Resistance.
SRL Shut-Down Relay.
ST Start Contactor (A.C.).

T Transformer.
TDR Time Delay No-Volt Relay.
TR Time Relay.

PRINCIPLES OF AUTOMATIC MOTOR CONTROL.

INTRODUCTION.

DURING the last twenty years, big developments have taken place in automatic motor control, chiefly in consequence of the demand for increased reliability of certain electric control operations necessary for modern production methods. The failure or wrong operation of one small auxiliary motor alone can upset the whole operation of a production line, with serious loss of time and material.

To avoid this, the hand-operated starter in many cases has been replaced by the automatic starter, which will control a motor either by push-button operation or automatically, as the demand for mechanical energy arises.

On the other hand, the flexibility of electric drives, with their many possibilities of speed control, rapid reversal of rotation and quick and effective braking, has opened up vast new fields for electric control gear.

In the following pages the principal features of automatic motor control are explained in order to show what can be done with the aid of modern contactor-type switchgear.

The illustrations and several of the diagrams are published by permission of Messrs. Brookhirst Switchgear Ltd.

CHAPTER I.—ELECTRIC MOTORS.

(1) Direct Current Motors.

Theory.

In principle, every motor is based on the fact that a conductor through which an electric current is passing is subjected to a mechanical force when in a magnetic field. If the conductor forms a loop, this force will produce a torque, tending to turn the plane of the loop until it is at right angle to the magnetic field. In this position the torque is zero, whilst its maximum value is reached when the plane of the loop is parallel to the magnetic field lines.

To produce a continuous rotation, a number of loops are required, arranged symmetrically around a common axis and energised in turn. This is controlled by what is known as the commutator.

In most cases the field is provided by a magnetic frame, with poles protruding towards the centre and provided with electric excitation windings. The magnetic circuit from one pole to the next of opposite polarity is closed through the armature, which carries the electric conductors placed in slots in its periphery.

The torque T will then be

$$T = C_M \cdot I_a \cdot \Phi \qquad (1)$$

I_a = Armature current.
Φ = Field strength.
C_M = A constant, depending on the design of the motor.

A further important feature to be considered is the "generator effect." A conductor moved in a magnetic field in such a way that during its movement lines of force are cut will produce a potential difference (P.D.) at its ends which, if joined together to form a closed electric circuit, will cause a current to flow. This P.D. depends on the speed of movement, the active length of the conductor and the density of the field lines :

$$\text{Electro-Motive Force E.M.F.} = L \cdot \Phi \cdot v$$

Thus the voltage across the brushes of a generator is

$$E = C_G \cdot \Phi \cdot n \qquad (2)$$

n = Number of revolutions per minute.
C_G = A constant, depending on the design of the generator.

If a motor armature starts to rotate, due to the effect of a current passing through the armature, an E.M.F. is automatically induced in the windings of the latter, opposing the applied voltage.

According to Ohm's law :

$$E - e = I_a \cdot R_a \qquad (3)$$

E = Applied voltage.
e = Induced E.M.F. in the armature.
I_a = Armature current.
R_a = Armature resistance.

$$\text{Since} \quad e = C_M \cdot n \cdot \Phi$$

$$E - I_a \cdot R_a = C_M \cdot n \cdot \Phi$$

$$n = C_M \cdot \frac{E - I_a \cdot R_a}{\Phi} \qquad (4)$$

Equations 1 and 4 form the principal equations with the aid of which the various types of D.C. motors can be easily explained and understood.

From 3 follows :

$$I_a = \frac{E - e}{R_a} \qquad (3a)$$

This means : at standstill with n = zero and $e = 0$

$$I_a = \frac{E}{R_a};$$

at full speed e rises to a considerable value, and I_a is correspondingly reduced.

It is important to understand the results caused by variation of either E or Φ. The former can be varied by inserting resistance in series with the armature or by other means described later on ; the second by either altering the magnetic resistance (very rarely done) or by variation of the current flowing through the windings of the field poles (I_e = excitation current) by inserting an adjustable resistance in series with the field winding.

Additional resistance in the field circuit means less effective magnetising effort (called "ampere turns") and therefore a reduced Φ. According to equation (3a) a small variation in e will produce a large variation of I_a, provided the applied E.M.F. E is constant. The product of Φ times I_a will therefore increase, *i.e.*, the torque will increase and accelerate the motor armature until a speed is reached where I_a, e and Φ balance again. Due to the acceleration, e increases and I_a is reduced again to such a value that the torque produced by Φ and I_a is just sufficient to overcome the load torque. The final value of I_a will be higher than the original I_a. The same consideration can be made for an increase of I_e (stronger field) and will show that I_a has been reduced as well as the speed. Thus, a stronger field will produce a lower speed and a weaker field a higher speed. Equation 4 proves mathematically what was found by logical deduction, viz., that the speed is inversely proportional to the field strength. This equation also indicates that n is directly proportional to E. Assuming Φ constant, an increase of E will effect an increase of n and *vice versa*. These two facts are used for starting electric D.C. motors and for controlling their speed.

In the case of a generator, an increase of I_e and thus Φ will result in an increased voltage, provided n is constant. A variation of E could also be effected by varying n with Φ constant, but this method is not generally practised on account of certain difficulties and disadvantages (bad commutation, reduced efficiency at low speed, uneconomic use of the prime mover, etc.).

Motor Types.

The various types of D.C. motors are obtained by the different methods employed for exciting the field. The simplest form is the

separately excited motor with field and armature fed from two separate sources. If field and armature are fed in parallel from the same supply, we speak of a "shunt-wound" motor, and if the field is excited by the armature current, a type known as the "series-wound" motor is obtained. In the first and second case the exciting current is independent of the load and the field-strength practically solely dependent on the supply voltage. Since the speed of a motor at constant supply voltage depends on the field strength, such a motor will show a constant speed-load characteristic. Rotating with no mechanical load, the armature current will be just high enough to balance the "no-load" losses, *i.e.*, windage, friction and ohmic losses in the armature. With increasing load, the armature current increases automatically in proportion, the speed still being practically constant and this process would continue until destruction of the armature took place.

The field strength of the series motor is not constant, but varies with I_a, which depends on the load. A heavy load will demand a high current, providing a strong field, and a light load will only produce a weak field, and therefore the speed will vary with the load. Theoretically, the speed should reach an infinite value at no-load, but windage, friction, etc., will always force a small current to flow and the field therefore is never really zero. This "run-away speed," as it is termed, practically never exceeds four to five times the rated speed, but as the centrifugal force increases with the square of n, this excess speed could certainly severely damage the motor. Similarly, if a shunt-wound motor were suddenly deprived of its field by breaking of a connection or failure of the field supply, the speed would rise to a dangerously high value and the armature current would also increase, and not only mechanical but also electrical destruction would be the result.

The shunt-wound motor, tending to operate at practically constant speed, lends itself to ordinary line-shaft drives, etc., whilst the series motor with the speed depending on the load and possessing a very high starting torque is chiefly used for traction and hoisting purposes. It is certainly unsafe to use it for belt-drives, due to the possibility of a sudden disappearance of the load.

A combination of the two motor types is known as the "compound wound" motor. Usually the series field is only small in comparison with the shunt field and two types are possible ; the two fields assisting each other or opposing each other.

Counter-compound-wound motors, with the two fields opposing each other, are of far less importance than the cumulatively compounded motors, with the two fields assisting each other. The latter have a speed-load characteristic which shows a decline with increasing load due to increased field strength and reduced n. This type of motor is used where sudden load peaks may occur, *e.g.*, for driving punches, shears, etc.

Starting.

With the motor at standstill, the current should theoretically reach the value

$$I_a = \frac{E}{R_a}$$

but in practice only 60 to 70 per cent. of this is reached, due to the inductance of the armature, and due to the fact that after the delay, when the full value of I_a should be reached, the motor armature has already started to move and induces a small back-E.M.F. However, only very small compound-wound motors up to about $\frac{1}{4}$-H.P., and series motors up to about 4-H.P. can be safely switched straight on to the lines; larger motors and shunt-wound motors could be seriously damaged by doing so.

To prevent I_a rising to a dangerous value, E has to be reduced. A method of doing this is to feed the motor armature from a generator driven at constant speed, the field of which is gradually raised from zero to its full value, whilst the motor field is fully energised and constant. This increase of E can be done in many steps, and consequently E will gradually increase to its full value. This method is called "Ward-Leonard" control of a motor and is adopted for starting and speed control of motors ranging from the smallest to the largest sizes. Its chief disadvantage is the necessity for three (and if a separate exciter is used even four) machines in place of only one. The advantages on the other hand are manifold and one of them is the very smooth speed control and starting.

For starting, a reduction of E can also be achieved by inserting a series resistance in the armature circuit. This is wasteful, but since the starting period is only a relatively short one compared with the time the motor will run at full speed, the over-all efficiency of the plant is not affected.

To allow for a good and rapid acceleration, I_a is permitted to rise above the normal current. The ratio : starting peak current to normal current is called r, the peak factor.

$$r = \frac{I_{maximum}}{I_{normal}} = 1{\cdot}5 \text{ to } 2 \text{ and more *}$$

With one step of resistance the motor would only reach a certain speed, determined by the corresponding e and I_a, and then, if connected to the lines, would again cause a current peak, lower however, than if no resistance at all had been used. To avoid this peak, not all of the resistance is shorted, but a portion left in circuit, allowing the motor to accelerate still further. Then another part of the resistance is cut out and this process is continued until the motor has nearly reached full speed and only then

* For permissible ratios see B.S.S. 587.

is it connected to the lines. If m is the number of resistance steps and R_1 the first step,

$$r^{m-1} = \frac{E}{R_A \cdot I_M} = \frac{R_A + R_1}{R_A}$$

with I_M the maximum peak current. With r, m and R_A, R_1 can be determined, and with this the whole series of starting steps.

$$r = \frac{R_A + R_1}{R_A + R_2}$$

$$(R_A + R_1) = r \cdot (R_A + R_2)$$

$$R_2 = \frac{R_A + R_1}{r} - R_A$$

It can be seen that the steps $(R_A + R_N)$ form a geometric progression with r as quotient. Many abbreviated mathematical and geometrical methods have been developed to simplify the calculations.

It is practicable to limit the number of starting steps to 4 or 5 for ordinary-sized motors and to 2 or 3 for smaller ones and to permit a deviation from the correct progression. I_M may thus vary during the starting process, but by limiting the number of steps, automatic starting is greatly simplified. Only in hand-operated starters, where accurate acceleration of the motor depends on the operator, is the number of steps greater.

It is important that the timing during the starting process should be accurate if the motor is to accelerate smoothly. If the starting resistance steps were cut out too rapidly, the current peaks would be too high. Alternatively, if starting were too slow, the resistances might be in danger of burning out, since they are only short-time rated.

The timing should depend on the load of the motor. When starting against no-load the timing will certainly have to be shorter than when starting against a heavy load or against a load increasing with the speed. This question is especially important when a starter has to serve various purposes and there are a number of methods available to control the acceleration.

Speed Control.

(*a*) SHUNT AND COMPOUND-WOUND MOTORS.

As already described above, the speed can be controlled either by varying the applied voltage E, or by varying the field strength Φ. The decision as to which method should be employed rests chiefly on the speed range required and on the smoothness with which the change of speed should take place.

The usual range for ordinary rheostatic field control is about 2 : 1, but in special cases this can be extended up to 3 : 1 and more. It has to be borne in mind, however, that weakening of the field is followed by an increase of I_A if constant torque is required. That means that the section of the armature conductors must be increased in size and also the design of the motor must be such that the increased centrifugal forces can be dealt with safely. This means, the bigger the range required, the larger the motor size compared with a constant speed model.

Commutation is also affected, the weakening of the field making sparkless commutation more difficult.

The field regulators are usually tapped resistances, parts of which are shorted as less speed is required and *vice versa*. The grading of the steps can be either determined from a saturation curve of the magnetic circuit of the motor or some rough formulae can be used giving approximate values which are good enough for normal purposes. For ranges greater than 2 : 1, it is advisable however that the major steps at least should be scaled off a saturation curve.

If, however, the required range is in excess of 3 : 1, say up to 10 : 1, or even more, a different method of speed control is required, and E instead of I_e is varied. Several methods can be employed, one being the already-mentioned Ward-Leonard system with generator field control in order to vary the voltage applied to the motor armature. This may be combined with motor field control so that part of the speed range, *i.e.*, usually the lower portion, is covered by field variation of the generator, and the rest by motor field control with constant E.

Another method of varying E is to insert a series resistance as for starting. This method is wasteful and permits of downward speed regulation only and is employed merely for smaller motors. Also, the control is fairly coarse unless a great number of steps are provided. This means very bulky regulators, since the current to be controlled is relatively heavy. A further disadvantage of series resistance control is the poor regulations obtained when load is applied. This will cause the speed-load characteristic of the motor to assume a shape similar to the one of a heavily compounded motor, due to the voltage drop across the resistance produced by the motor armature current.

Another method for varying E makes use of a booster generator. In this case an auxiliary motor drives a generator which is connected in series with the main motor armature (see Fig. 45). By varying or reversing the generator field, the generator voltage is varied and either added to or subtracted from the supply voltage. Speed regulation is very smooth, even down to very slow speeds. It is easier to obtain stable low speeds than with Ward-Leonard control, where only a very weak generator field is required, whilst the

boosting (or in this case bucking) generator requires its full field. The disadvantage of the scheme lies again in the number of machines required and their size. It is usual to employ a generator set half the size of that of the main motor. The limit for the speed regulation is the size of the M.G. set and certain resistance conditions, which make a stable regulation at low speeds very difficult. Usual limits are 10 : 1 to 15 : 1.

In recent years two further methods of varying the applied armature voltage have been developed. One makes use of the grid-controlled rectifier (either mercury-arc rectifier or gas-filled hot-cathode valves), the other employs metal rectifiers and variable voltage transformers. Grid control of rectifiers can be used to produce some remarkable results, not only permitting very wide speed-ranges (up to 100 : 1) but also allowing extremely close regulation (± 2% for wide speed ranges and closer regulation where shorter ranges are required). In addition, current limiting and controlling features can be incorporated. The principles of this kind of motor control, however, far exceed the scope of this book and readers are referred to literature on electronic control for further details.

Metal rectifiers (usually of the solenium type) have a constant AC to DC transformation ratio, hence the need for variable voltage transformers for variation of the AC input. Speed ranges obtainable go up to about 80 : 1, shunt-motor characteristics being obtainable at the higher ranges, but the characteristic becomes more drooping at the lower ranges, due to the inherent regulations of rectifier and transformer. It is possible to combine shunt-field control with armature voltage control, either by splitting the speed range and using armature voltage control for the lower speeds with field control for the higher speeds or by employing an auxiliary winding on the transformer, producing a variable voltage which, rectified, will provide variable shunt-field control simultaneously with variable armature voltage.

One important fact, however, especially in the case of the field regulator, is, that during starting the motor must have its full field to assist acceleration and to prevent excessive armature currents. To ensure these conditions it is essential to incorporate certain interlocks or to provide special apparatus which control the field automatically and short-circuit the field resistance during starting, permitting the motor to accelerate to the minimum speed and then, after this has been reached, to gain the speed previously set on the regulator. Such components are known as speed relays, field relays or accelerating relays.

To ensure smooth resistance control in the field circuit, two regulators can be employed, a coarse main regulator and a fine vernier regulator, which subdivides each step of the main regulator

into a number of smaller steps. Start-interlocks in such a case are only provided for the main regulator.

(*b*) SERIES MOTORS.

The same methods as described above can be employed also for this kind of motor. Field control, however, is not easily effected, since the excitation current is identical with the main armature current, which does not permit of the use of field regulators.

It is possible to use a diverter resistance for the field and to obtain a certain field variation in this way, but this method is limited to comparatively small speed ratios.

Variation of the applied voltage is the chief means of obtaining satisfactory speed control and this can be done either by resistance in series with the armature or by employing an M.G. set. Resistance control is wasteful and therefore only used either with small motors or in connection with drives where efficiency is of no importance, *e.g.*, drives which have to run only occasionally with reduced speed. An upward speed regulation by this method is impossible.

Shunting of the armature by diverter resistances is also possible, but results not only in varying the speed but in changing the motor characteristic. Such schemes are employed on cranes and hoists to provide safety lowering and to guard against excessive lowering speeds under too heavy loads.

Reversing.

Since the torque of the motor depends on the interaction of I_a with the field Φ, reversal of rotation can be effected by reversing either I_a or Φ.

In order to preserve the residual magnetism of the motor or generator, it is advisable to reverse the armature connections since the reversal of the field of a self-excited, shunt-wound generator will result in failure to excite. Reversal of the rotation of a generator is not advisable, as this may affect the commutation.

Rapid reversal of motors necessitates special constructions, since serious mechanical and electrical stresses will occur. At the moment of reversal the motor is still continuing to run in the former direction and the back-E.M.F. will be added to the line voltage, raising the motor voltage to nearly twice the ordinary value. The motor will work as a generator and return energy to the mains, and with no other resistance in circuit than series field and armature resistance, the current could reach very dangerous peaks. This regenerative-braking will reduce the speed very rapidly to zero and then the motor is restarted in the opposite direction.

To minimise shocks and heavy current peaks, resistance is usually connected in series with the armature as for starting. This

is also required for the restarting of the motor in the opposite direction. Instead of using regenerative-braking, dynamic (or rheostatic) braking of the motor may be applied before restarting.

Braking.

All electric braking processes make use of the fact that a motor, mechanically driven, will act as a generator and convert mechanical energy (inertia of rotating masses, lowering of a load, etc.) into electrical energy, which can be either returned to the mains or destroyed in resistances.

(*a*) Regenerative Braking.

A shunt-wound motor, driven mechanically in the same direction in which it was running when motoring, will develop an E.M.F. opposing the line voltage, and if speed and field conditions permit this induced E.M.F. to be higher than the line voltage, energy will be returned to the mains. This will continue as long as the generated E.M.F. is higher than the supply voltage, but as soon as this condition ceases to exist no more braking will take place. This limits the application of this method.

A series motor, driven mechanically, does not act as a generator straight away. With the application of mechanical energy the armature current will reverse its flow, but this also causes the reversal of the field current. The reversed field would reverse the armature E.M.F. again and this process would continue without energy being returned to the lines and consequently no braking torque would be developed. Apart from this, the reversal of the field currents might destroy the residual magnetism of the motor and no self-excitation would take place. In order to effect regenerative braking, the armature connections will have to be reversed. Since the voltage of a series generator depends on the speed it is very difficult to obtain good braking results and this kind of braking is generally not applied to series motors.

Because of the difficulty of obtaining stable braking results, regenerative braking is not often used for industrial drives.

(*b*) Dynamic or Rheostatic Braking.

Instead of returning electrical energy to the mains, it can be destroyed in braking resistances. This kind of braking is called dynamic or rheostatic braking, and is very effective. The braking torque can be varied by altering the resistance in circuit and thus also the braking current can be controlled.

No special precautions are required when braking shunt-wound motors, but for reasons described above, the armature connections

of a series motor will have to be reversed to allow it to act as a self-excited series generator. On the other hand, care has to be taken to ensure a field supply for a shunt-wound motor, since no braking would take place without a field. The field can be supplied either from the mains or it can be connected across the armature terminals. In the first case the field remains constant and independent of the speed of the motor, whilst in the second case, with decreasing speed, also the generated E.M.F. and thus the field itself is reduced, resulting in a more rapid decrease of the braking effect. If dynamic braking is applied to compound wound motors, the compounding field is not included in the brake circuit and is not energised during braking.

Braking to a standstill is not possible by this method. There will always be some resistance in circuit (armature, leads, brushes, etc.), thus only allowing braking down to low speeds when no more effective braking torque is developed.

It is common practice with larger motors to provide a series of steps of braking resistance to keep the torque approximately constant. With decreasing speed and correspondingly decreasing armature current, the resistance is gradually cut out. By sacrificing theoretically correct steps the starting resistance can be suitably adapted for this purpose.

(*c*) SOLENOID BRAKING.

This is a mechanical braking method where an electrically-energised solenoid lifts a brake lever against the action of a weight or spring. Failure of supply or de-energising of the solenoid will cause application of the brake.

(*d*) BRAKING OF M.G. SETS.

Regenerative braking can be easily applied to a Ward-Leonard set by reversing the generator field. The field current will require some time to build up the field due to the inductance of the circuit, and thus the braking effect will not be so sudden and severe as with armature reversing.

Regenerative braking can be applied to Ward-Leonard and to booster control, but special precautions have to be taken against overloading the dynamos.

(2) Alternating Current Motors.

Theory.

The same principles which are valid for D.C. motors apply to A.C. motors, although the methods used to achieve the same results are many and varied, hence the number of A.C. motor types.

Motor Types.

(*a*) Commutator Motors.

These are a copy of the corresponding D.C. machines (either series or shunt wound), with the necessary alterations which the A.C. supply enforces.

A.C. single-phase series motors are in use as traction motors. The single-phase, shunt-wound variety, however, has lost its importance with the development of the self-starting, single-phase induction motor.

Poly-phase commutator motors are in use in the shunt-wound form for variable speed drives, whilst the series-wound type is occasionally used for hoists and cranes. There are a number of shunt-wound types available with different characteristics and different methods of speed control and power factor compensation. Speed control is smooth and stepless if brush-shifting gear or induction regulators are used, the speed ratios being up to 10 : 1. Reversing of the motor is possible, but cannot be done as quickly as with A.C. driven M.G. sets (see later). The brushes or induction regulators have to be returned to the neutral position before re-starting in the reverse direction is possible.

The movement of the brushes or of the induction regulator can be done either by hand or by a servo motor geared to the brush gear or the induction regulator. This motor is usually push-button controlled.

The chief disadvantage of the poly-phase commutator motors is their cost, which is greatly in excess of any of the other motor types.

(*b*) Synchronous Motors.

This type of motor is an inverted A.C. alternator and is similar to a D.C. motor, with the one difference that no commutator is provided to change the polarity of the armature windings.

A poly-phase system is capable of building up a rotating magnetic field if fed to windings, the magnetic axes of which are intersecting each other at angles different from 0° or 180°. Three windings displaced by 120° and fed by three-phase current will produce a constant rotating magnetic field. A single-phase A.C. field produced in a single winding can be split up into two equal rotating fields, rotating in opposite directions, so that the resultant magnetic field is a stationary field of varying magnitude.

The speed with which the field rotates is determined by the frequency and by the number of poles of the stator producing it. The higher the frequency, the higher the speed. The more poles, the lower the speed, because in a given time the field vector travels over a smaller angle in the case of many poles than it would in the case of fewer poles.

$$n = \frac{60 \, . \, f}{p} \qquad (6)$$

n = Number of revolutions per minute.
f = Frequency in cycles per second.
p = Number of pairs of poles, *e.g.*, one for a two-pole machine.

A magnet inserted in such a rotating field will be "caught" by it and rotate with it, provided it catches up with the speed of the field. This is due to the attraction of magnetic poles of opposite polarity, and one can imagine a rotating north pole of the electrically generated field taking hold of the south pole of the magnet and pulling it along as it goes round. This magnet can be a permanent magnet or D.C. excited.

Chief features of synchronous motors are absolute constancy of speed, depending on the supply frequency; need of external appliances or other means to accelerate up to nearly full synchronism, so that "catching" or "falling in step" of the magnet can take place; mechanical overloading can produce "falling out of step," which would result in stopping the motor; variation of the D.C. excitation current only influences the power factor.

This kind of motor requires auxiliary means for starting and a separate D.C. excitation. It can be made self-starting by addition of a short-circuited winding, required also for some other important purposes. In this way it will start up as an ordinary induction motor with short-circuited rotor (see later), and when synchronism is nearly reached, the D.C. excitation winding is energised and pulls the motor into step. Another method employs special starting motors (A.C. induction motors), for which purpose also the D.C. exciter could be used if a D.C. supply were available.

(c) INDUCTION MOTORS.

These are by far the most numerous A.C. motors used. The motor consists of the stator, with the stator winding, required to produce a rotating field as for the synchronous motor. The rotor carries another winding, which may be either internally short-circuited or the ends of which are brought to slip-rings which can be shorted by some external device. Assuming the stator energised, and the motor at standstill, the rotating field will cut all the rotor windings at full speed and induce an E.M.F. in them. Provided the circuit is closed, this E.M.F. will drive a current through the windings which will develop a torque in conjunction with the primary field and cause the rotor to move. At standstill the rotor frequency will be the same as the stator frequency. With increasing speed the rotor frequency and voltage decrease, due to the decreasing relative speed of rotor windings and rotating field. The motor will only accelerate up to nearly synchronous speed

(hence the second name for this kind of motor, "asynchronous" motors). At synchronism, no cutting of field lines by the rotor conductors will take place, and no E.M.F., no current and no torque will be developed. The rotor will therefore have to remain at slightly below synchronous speed to allow the flow of a current sufficient to develop a torque to cover all the losses. An increased load torque will result in a further slight decrease of the speed to allow more current to flow in the rotor windings. The difference in speed between primary, rotating field and rotor speed is known as the slip, and is expressed in a percentage of the synchronous speed. Usual full-load values for the slip range between 2 and 5 per cent., depending on the size and kind of motor.

The speed is practically constant and cannot be varied, as it depends solely on the supply frequency and the number of poles of the motor.

Characteristic features of this kind of motor are :—constant speed ; self-starting ; high-starting torque, especially when started straight across the lines ; good acceleration ; robust design ; cheap ; relatively poor power-factor, especially during starting and at light loads.

Since the rotor windings can be shorted internally, they can be of a very simple design and often only consist of two copper-rings connected by copper rods placed in slots of the rotor. This type of motor is known as the "squirrel cage" motor.

If the ends of the rotor windings are brought to slip-rings from which the current can be taken off by means of brushes, the motor is called a "slip-ring" or "wound-rotor" induction motor. Usually the windings are starred at one end and the three other ends are each brought to a slip-ring.

(*d*) SYNCHRONOUS INDUCTION MOTOR.

This motor is a combination of a synchronous and a wound-rotor induction motor. It is provided with a separate exciter and started in the ordinary way as an induction motor. When reaching its full speed, slightly below synchronism, a D.C. excitation current is fed to the rotor windings (to one or two phases only) and the motor is pulled into step and continues to run as a synchronous motor. It possesses good starting characteristics, has a good power factor during running (adjustable as in the case of a synchronous motor), and under mechanical overload conditions, forcing it out-of-step, it continues to run as an induction motor until the overload is passed and then regains synchronism.

Starting.

This depends entirely on the type of motor, whether this is a squirrel-cage induction motor, a synchronous motor or a wound-rotor induction motor.

In the latter case, insertion of external resistance in the rotor circuit will have the same effect as with a D.C. motor—reduction of the rotor current and thus of speed and primary current. It means wasting of energy, but it is the only way to start an induction motor gradually whilst developing full-load or higher starting torques. To reduce brushwear and losses during running, the brush gear can be lifted off the slip-rings and these are short-circuited internally. To ensure that this short-circuiting connection is removed before starting, and that the brushes rest on the slip-rings, special interlocks are required. In automatic start-control schemes, however, little use is made of such a device, since it means the introduction of some manual function in the starting process.

Different methods are used to start a squirrel-cage motor. The simplest is "straight-on starting," when the stator is switched directly on to the lines. The current will reach 4 to 7 (and in some cases up to 14) times the rated value and the developed torque is about 1 to 2 times the normal torque, both values depending entirely on the design of the motor. This method is applicable to all sizes of motors, from the smallest to the largest.

If the supply authorities do not allow the straight-on starting of larger motors on account of the heavy initial current peak, the voltage has to be reduced when switching on the stationary motor in order to reduce this peak. The torque is also reduced in proportion to the square of the applied voltage.

This reduction of the voltage can be achieved in various ways. Inserting resistances is sometimes done, but it is wasteful and produces only low-starting torques. Generally, only small motors are sometimes started in this way, having one step of starting series-resistance. A more economic method is the use of starting-transformers, usually auto-transformers. They are provided with one or two tappings to provide one or two starting steps before the motor is connected to the full supply voltage. This starting voltage usually varies between 40 and 70 per cent. of the full voltage.

Another method makes use of the various possibilities of connecting multi-phase motor windings. Fig 1 shows how an ordinary

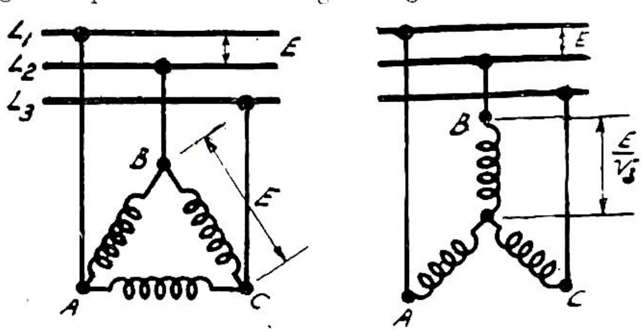


Fig. 1.

three-phase motor can be connected either in star or in delta and since the supply voltage is in both cases E, the voltage across the phase windings will be $E/\sqrt{3}$ when star connected and E when delta connected. Thus, by a simple switching operation, two voltages are available, one for starting and one for running. Reduction of the starting torque to about one-third of full-load torque, however, must not be overlooked. A two-phase motor can be started in the same way, by winding each phase in two halves and connecting these first in series (half the voltage across each part of the winding) and then in parallel (full phase voltage across each part of the phase winding). The starting torque will be reduced to about one quarter of full-load torque. Phase and line-currents will also vary, and this has to be borne in mind when arranging for overload protection during starting.

Single-phase motors require special starting facilities. As described above, a single-phase winding produces a stationary field, varying in magnitude. This, however, can be split into two rotating fields of half the magnitude, rotating in opposite directions. A single-phase motor, once given a mechanical impulse in one direction, will soon be caught by the half of the field rotating in the same direction and continue to run.

For automatic starting, however, this method is inapplicable, and use is made of an auxiliary phase connected in parallel with the main phase, but of different impedance. This is achieved by inserting in series with this auxiliary winding a choke-coil, a condenser or a resistance. Thus the phase angle of the field produced by the auxiliary phase is different from the main field and the two fields together produce a rotating field, thus permitting self-starting of the motor. The auxiliary phase is disconnected after starting, either by centrifugal switches or by time-controlled switching devices. These switches will disconnect the auxiliary winding after the motor has reached nearly full speed.

A different method of ensuring automatic starting of a single-phase motor is the use of shaded poles. A heavy short-circuited winding is put round part of the pole-face, thus displacing the phase-angle of the part of the field passing through this winding and with the aid of this displaced field a rotating field is set up.

Addition of ohmic resistance in the rotor windings not only facilitates starting, but also improves the torque conditions, since the phase angle between rotor current and field is reduced. With wound-rotor induction motors, heavy starting torques can be produced, considerably in excess of any torques available from ordinary squirrel-cage motors. These starting resistances are stepped similar to D.C. starting resistances and form a geometrical progression.

Speed Control.

As described above, inserting resistance in the rotor winding of an induction motor decreases the speed. This method is often employed to reduce speed, but speed reduction is never extended beyond a range of 10 to 20 per cent. because of the resulting waste of energy.

Another method of varying the speed is frequency variation. This method, however, is not easy, since it involves separate machines for the frequency control and is used only in special cases.

Alteration of the number of poles also influences the speed. Special windings have been designed which allow a change in the number of poles in the ratio of 1 : 2. This can be effected by changing the motor connection in a certain way (see Fig. 20). A simpler method is to provide one motor with two stator windings for two different number of poles, again in the ratio of 1 : 2, but this usually necessitates a bigger motor frame. To obtain ratios of 1 : 2 : 3 or 1 : 2 : 3 : 4, combinations of these two methods are used, viz., two windings are employed, the number of poles of which can be varied.

Another method of speed control is the "cascade" connection of induction motors with other wound rotor induction motors, A.C. commutator motors or rotary converters which allow either a limited number of steps (2 or 3), or a wider ratio over which the speed can be carried gradually, even above synchronism. All these systems are very elaborate and expensive and are only in use for big motors.

Braking.

An A.C. induction motor driven above synchronism will act as a generator, and this fact can be used for regenerative braking. This, however, can take place only above the ordinary working speed.

To brake induction motors to a standstill, two other methods are usually employed, viz., ordinary A.C. "plug" braking and D.C. injection braking.

In the first method the direction of the field rotation is reversed. Thus the slip is suddenly changed from +2 to 4 per cent. to −200, and a good braking effect is achieved. This will gradually increase as the speed decreases, and at 100 per cent. negative slip the rotor is at stand-still, develops full starting torque and if nothing is done to prevent it, will commence to accelerate in the reverse direction until -2 to -4 per cent. slip is reached. Special relays or centrifugal switches are used for stopping the motor before it commences to reverse.

Wound rotors with low resistance, which are required for quick reversing duty to give good acceleration, will have a very flat torque-slip characteristic and the plug-braking torque will be

very low. To increase this, external rotor resistance is inserted, changing the torque characteristic in such a way as to increase the braking torque to a suitable value.

Sometimes it is found that the current peaks when braking are very high, and to reduce these, primary resistance is inserted. This also affects the braking torque, which is reduced correspondingly. (At constant slip the torque varies with the square of the voltage).

Reversal of the field can be obtained by reversing two of the three connections of a three-phase stator or by reversing one phase of a two-phase system.

D.C. injection-braking makes use of a D.C. energised stator which produces a strong stationary field in which the short-circuited rotor moves. The effect is similar to D.C. dynamic braking. In the case of low-resistance wound-rotor motors, it will be necessary to insert external rotor resistance to limit the current in the windings which, due to the low resistance, would otherwise reach very high values. This high current will react on the primary magnetic field and tend to weaken it and thus make the braking less effective. The motor current will have to be adjusted to an optimum value by external rotor resistance, so that it is neither too high to weaken the field nor too low to provide satisfactory braking.

CHAPTER II.—SWITCHGEAR.

(1) Contactors.

These form the backbone of automatic control gear. Originally only used to open and close electric circuits by the operation of a pilot switch, their functions have since been multiplied.

Generally, the same principles are used for A.C. and D.C. contactors, and the final design varies only in details due to the different requirements of A.C. and D.C.

There are three main groups of electrically-operated or controlled contactors :—

(1) Electro-magnetic contactors.
(2) Pneumatic or hydraulic contactors with electric control.
(3) Cam or otherwise operated contactors (switches).

Each group can be again subdivided according to the duties performed or the number of poles, etc.

In its simplest form the electro-magnetic contactor consists of a solenoid, lifting a plunger to close a switch. This type is still used for small contactors or special designs, but the large majority of contactors make use of the clapper-type magnet, where the armature describes a semi-rotating movement.

Of the three groups mentioned, the first is the one chiefly employed in automatic schemes. Hydraulic or pneumatic contactors are operated by plungers, controlled by gas or fluid pressure, the flow of which is governed by electro-magnetic valves.

Mechanically-operated contactors or switches are used for heavy starting gear or for the control of certain operating cycles, repeatedly required. The cam-shafts are either hand-operated or driven by a pilot motor. Also ratchet drives in combination with electro-magnets have been used for that purpose.

The design of the contactor depends very much on the required duties, hence single-throw, double-throw, normally open and closed contactors, with shunt or series coils or with both, etc. They have to be of a very robust construction to withstand severe operating conditions. and the design will be greatly influenced by the type of duty for which the contactor is intended (see B.S. 775).

The pull of an electro-magnet in the closed position is obtained from the formula :—

$$P = \frac{B^2 . A}{8 \pi}$$

P = Pull in dynes.
B = Flux density in lines per square centimetre.
A = Area in square centimetres.

In the open position, the pull depends largely on the air gap. the shape and size of the pole pieces, and whether A.C. or D.C. flows through the coil.

P is proportional to the square of the current flowing through the excitation winding. With the armature in the open position, the magnetic path is interrupted by the air-gap, thus reducing the flux due to the latter's high reluctance. A D.C. magnet coil has a constant resistance, independent of the magnetic circuit, hence the excitation current is the same in the open and closed position. Due to the considerably decreased flux in the open position, when the majority of ampere-turns will be required to overcome the magnetic resistance of the air-gap, the pull will be only a fraction of the pull in the closed position. To overcome this, the current may be allowed to be higher (up to 4 times normal current) in the open position than would be permissible for the coil. Once the armature has closed, the coil current is reduced to a safe value, sufficient to hold the contactor closed. This reduction of the current is done by inserting a series resistance in the coil circuit, this resistance being short-circuited in the open position. It is usually termed "Economy Resistance," and the switch inserting it, "Economy Switch." This switch has to open on the very last movement of the armature.

An A.C. magnet coil shows different characteristics. The excitation current depends on the impedance of the coil, which in

turn depends on the magnetic path. With a long air-gap, the magnetic resistance is increased, accompanied by a greatly reduced reactance. In the open position, therefore, the impedance will be greatly reduced, permitting a high current to flow through the coil. This will be automatically reduced to a safe value as soon as the armature has closed, due to the increased reactance of the circuit. The heavy initial current will provide a comparatively high pull-in torque in contrast to the D.C. model.

D.C. contactors are usually provided with a short air-gap and are, especially in the larger sizes, of single-pole design with the main pole mounted above the armature and extended to allow a larger arc of movement. A.C. contactors are usually of the multi-pole type, and the radius of movement of the contacts is about the same as that of the armature.

Another point where A.C. and D.C. models differ is in the construction of the magnetic frame. Mild steel or cast-iron is used for D.C. contactors, whereas laminations of special alloy-steel, insulated on one side, have to be used for A.C. to cut down eddy-current losses and losses due to the de- and re-magnetising effect of the A.C. voltage. Care has to be taken to avoid the formation of any closed metallic circuits around the whole or part of the core or armature, chiefly by rivets or other parts used for clamping the laminations. Due to the transformer effect, these circuits would act as short-circuited transformer windings, with a subsequent very heavy current flowing in them which could not only destroy these parts, but would also cause loss of energy.

The flux of a single-phase A.C. magnet varies according to the applied voltage and passes through maximum and zero values twice per cycle. Thus the armature will have a tendency to drop out and reclose in the same rhythm and produce a very loud and disagreeable "hum." To avoid this, part of the flux is made to pass through a short-circuited winding, called "shading ring." This retards the enclosed flux in phase and prevents a zero in the total pull, thus quieting the armature. With larger models it might be necessary to reduce the current in these shading windings by either inserting resistance or by making the rings themselves of a material of higher resistance.

The movement of the armature of a D.C. contactor will produce a counter E.M.F. in the excitation windings, thus retarding either opening or closing. An A.C. magnet will not be affected in this way and has shorter opening and closing times.

A further important item is residual magnetism which might cause "sticking-in" of a D.C. contactor. By making the armature heavy and the compression springs of the butt-contacts strong, this effect can be partly overcome. The most effective counter-measure, however, is the incorporation of a short air-gap to prevent

the establishment of a completely closed magnetic circuit. This air-gap is produced by non-magnetic (*e.g.* brass) shims or screws.

Comparison between A.C. and D.C. Contactors.

A.C. (See Fig. 2).	D.C. (See Fig. 3).
Tends to noise, rapid opening and closing, automatic reduction of coil current, good initial pull, long air-gap, multi-pole design, difficult to provide more than one winding on the same core due to transformer effect, laminated construction.	Quiet, sluggish opening and closing, require economy resistance and switch in many cases, poor initial pull, short air-gap, single-pole design usual. Easy to accommodate any number of windings on the same core, solid mild-steel or cast construction.

Simple butt-type contacts are only used for relays or A.C. contactors up to about 25 amperes. Usually they are of silver or silver alloy. Heavier contactors are provided with rolling butt contacts which close with a rolling action and establish a line-pressure contact. This rolling action prevents burning and pitting of the contacts at the point of contact, any arc being drawn at the tip, where the rupture of the circuit takes place.

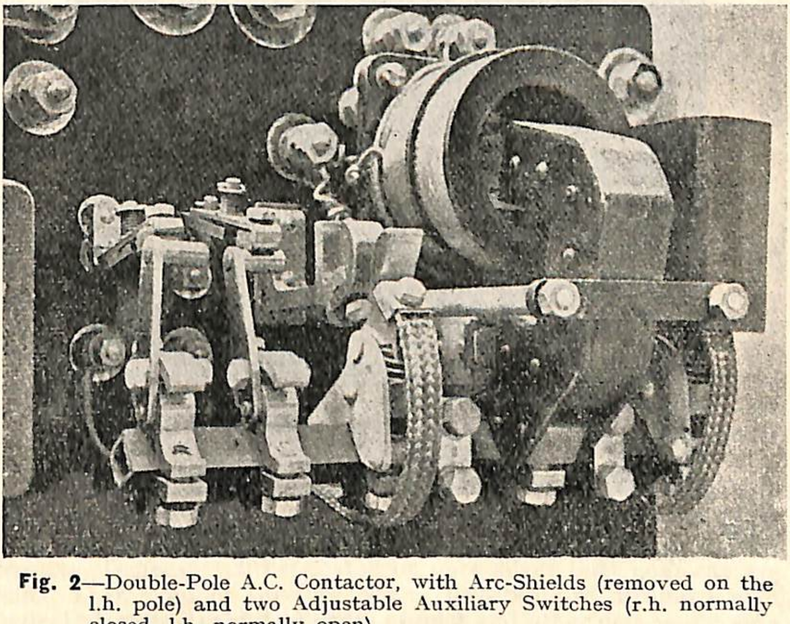


Fig. 2—Double-Pole A.C. Contactor, with Arc-Shields (removed on the l.h. pole) and two Adjustable Auxiliary Switches (r.h. normally closed, l.h. normally open).

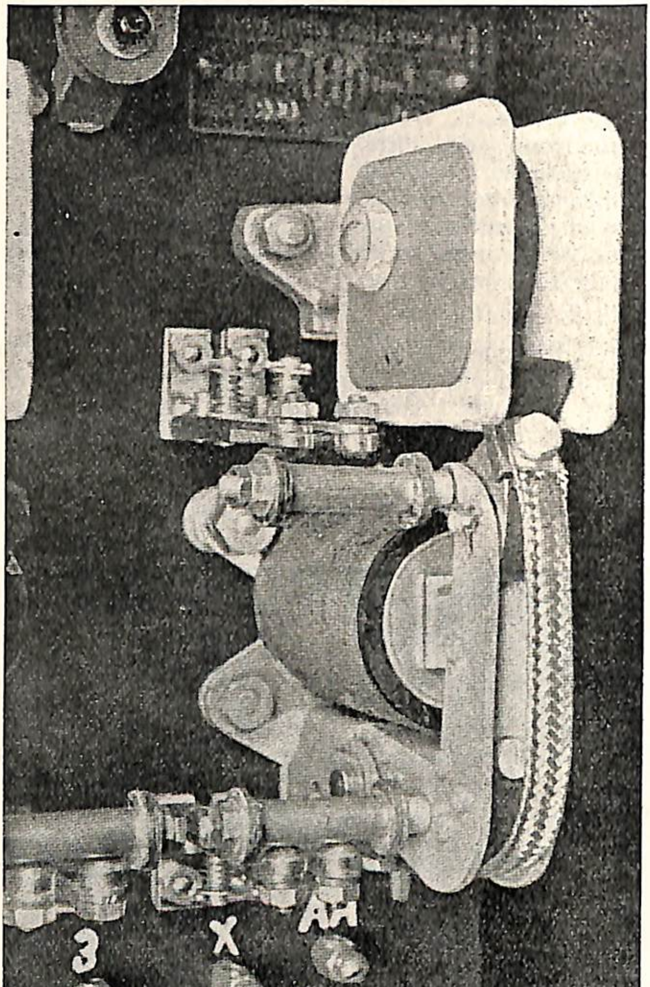


Fig. 3—D.C. Contactor. Single-Pole type, with Blow-out Coil, normally open and normally closed Auxiliary Switch.

Only large models (about 1000 amperes and over) are sometimes equipped with brush-type main contacts, and as these are not suitable for interruption of a circuit, special arcing contacts have then to be provided.

Flexible connections (chiefly braided copper) connect the moving contact to a terminal on the panel.

Electro-magnetic blow-outs are very often used. D.C. models are nearly always provided with them. They also find increasing use on A.C. contactors where frequent operation is required or currents with low power factors have to be dealt with. They increase the rupturing capacity and facilitate the rapid extinction of the arc, thus reducing contact wear.

A phenomenon liable to occur with spring loaded contacts is bouncing during closing. The kinetic energy of the moving contact causes elastic deformation of the fixed contact at the moment of impact and, in turn, causes the moving contact to be repelled against the action of the contact spring. A similar action may cause a rolling butt contact to roll back further than its normal closed position. In both cases it is possible for the two contacts to separate momentarily. The contact spring will return the moving contact, but the action may be repeated several times before the contact finally comes to rest. The breaking of the circuit will cause short but powerful arcs to be drawn between the two contacts which will heat up the contact surfaces and, under the pressure of the contact spring, could produce welding. Contact wear is also increased due to the arcing. By careful design it is possible to minimise the possibility of bouncing.

The various forms of contactors will be discussed separately in the respective chapters.

(2) Auxiliary Contacts.

These should be just as robust and strong as main contacts, so that they can deal safely with all the auxiliary circuits. All three contact varieties are required—normally open, normally closed, and change-over, the latter being either of the make-before-break or the break-before-make type. The switches can be made adjustable, so that opening or closing takes place before or after a certain other switch has operated. Sometimes toggle-switches are used to give rapid and definite operation with a minimum of movement, as, *e.g.*, in the case of economy switches.

Self-aligning contacts are often used. A certain amount of movement between fixed and moving contacts takes place, providing a "wiping" action and thus cleaning the surface and ensuring good contact. Generally, silver-plated or pure silver butt contacts are used. Their contact surfaces, where possible, are arranged in a vertical plane to avoid deposition of dust and other non-conducting

particles. Particularly at low voltages (below about 120 volts) this deposition can be troublesome and may cause contact failure.

The number of auxiliary switches which can be fixed to one contactor is limited by the pull of the armature. Usually, four to five switches are the maximum and in case more are required, multiplying relays are used, controlled either by a switch on the main contactor or having their operating coil connected in series or parallel with the contactor coil.

(3) Interlocks.

These are devices either causing or preventing a change in the electrical or mechanical condition of the whole control unit, if one contactor or other component part is operated. Such interlocks are, *e.g.*, interlocks between door of cubicle and isolator or interlocks between two or more contactors to prevent one closing when the others are closed, etc.

These interlocks may be of two types, *i.e.*, mechanical or electrical. Very often both are used simultaneously to guard against the failure of one.

Electrical interlocks are discussed in a later chapter. Mechanical interlocks usually consist of a lever arrangement of sturdy design. They should be definite in operation and even if both interlocked components start movement simultaneously, it should prevent them from closing but should not jam.

Very often interlocks are required to ensure tripping of a contactor if, for instance, the door of the cubicle is opened or the isolating switch operated with the contactors closed. This, again, can be done electrically or mechanically. The latter is sometimes preferable, due to the quicker action. The time delay in the electric circuit required for the building up or destruction of electromagnetic fields may cause the main current to be broken on the isolator instead of on the contactor.

(4) Special Contactor Types.

(*a*) Latched-In Contactors.

This type of contactor is provided with two coils, a closing and a tripping coil. The first is only energised for closing, and a switch interrupts the circuit of this coil once the contactor has closed. It is held closed mechanically by a little catch which is linked to the trip-magnet armature. As soon as the trip magnet coil is energised, this armature closes and lifts the catch, thus freeing the contactor armature, which drops out. Both coils need only be short-time rated.

Latched-in contactors were originally developed for the control of boiler-house auxiliaries. Ordinary contactors were apt to trip out on the occurrence of transient faults and caused the shutting

down of the affected boiler. The latched-in contactor has lost these no-volt features. These are, of course, still required in many cases and separate no-volt relays, usually with a delayed action, have to be incorporated. (For example, see Fig. 22).

Very often either the tripping coil alone or both coils are D.C. operated from a separate supply each.

(*b*) Dynamic Brake Contactors for D.C. Motors.

These are of the change-over type, either double or single throw. The former is chiefly used for the smaller sizes, whilst both types may be used for higher ratings.

The double-throw variety is generally provided with a secondary coil which is energised either by the braking current or by the voltage drop across the braking resistance. Furthermore, main contacts are incorporated, which are closed, when the contactor is in the open position (an example of a scheme incorporating series energised hold-on coils is shown in Fig. 42). The secondary coil, usually called hold-on coil, is provided with its own magnetic path, the contactor armature for this purpose being extended below the bearing centre line. Two such contactors are required for a brake control scheme. When these drop out due to depression of the stop-brake button, the armature of the motor is short-circuited by the brake resistance through the normally closed contacts of the contactors. The hold-on coil is energised and pulls the contactor armature downwards, thus not only increasing the pressure of the closed contacts and ensuring good contact, but also making it impossible for the shunt closing coil (if re-energised) to re-close the contactor until the braking current has sufficiently subsided, so that the tractive force of the shunt coil can overcome the pull of the hold-on coil.

Small braking contactors are sometimes fitted with a strong tail spring to hold the contactor out. In such a design, the braking current has no influence on the contactor and the shunt closing coil has to develop sufficient pull to overcome the spring pressure.

(*c*) Lock-out Contactors.

Contactors of this type are generally used for automatic acceleration of D.C. motors and are for this purpose similarly designed to the brake contactors described above, with the exception of the normally closed braking contacts which are omitted. The hold-out coil is energised by the starting current (see Fig. 15) and prevents the contactor from closing under the action of the shunt closing coil until the starting current has dropped sufficiently to permit the next step of resistance to be short-circuited.

It is possible to adapt this type of contactor for A.C. use by employing metal rectifiers for converting the A.C. coil supplies to D.C.

(5) Relays.

The functions of relays are many, hence a great number of different designs exist.

The same principles which are valid for the design of contactors also apply to relay design. Multi-pole relays are used when, for instance, the number of auxiliary switches to be accommodated on the main contactor is too big, or for special control purposes (inching, accelerating, etc.).

Relays are also used in connection with control instruments (pressure gauges, temperature controllers), where the small and delicate instrument contacts could not deal with the comparatively heavy coil current of a big contactor. The small relay coil can be controlled easily by the instrument contacts and the relay switches then take care of the contactor closing and opening current. Relays are also employed for the control of automatic starters which are installed at a considerable distance from their respective control stations, requiring long lines of interconnecting cables. The contactors in such cases might give trouble when closing, due to the voltage drop in these cables produced by the coil current, and a relay interposed will remedy this, as it can be designed to close satisfactorily on a very light current which will not cause an appreciable drop in the long inter-connecting lines.

Relays may also have to be used to provide low-volt or no-volt features in certain automatic equipment, so that if the starter is tripped out due to one of these cases, automatic restarting after return of the supply voltage is prevented. The motor will only start again after a definite operation has been performed by the operator.

Low-volt or no-volt relays are also required in connection with latched-in contactors which have lost these features. The relay is then required to close the tripping circuit of the contactor if faulty supply conditions arise.

In connection with D.C. control schemes, a great number of special relays are required, *e.g.*, accelerating relays securing starting with full motor field and automatically accelerating the motor up to a present speed ; dynamic brake relays to ensure the maintenance of the motor field during the braking process ; excess voltage relays to trip the starter should the motor be driven by the load at an excessive speed (too high back E.M.F.), etc. All these relays are described in detail in the corresponding chapters.

A certain group of relays are those which are required to secure a pre-arranged time interval between two or more control operations. These relays make use of various electric, magnetic, mechanical or other physical phenomena in order to delay the opening or closing of a control circuit.

The simplest and oldest form of these time delay relays is the solenoid with the dash-pot which delays the plunger movement.

With the solenoid energised, the plunger is lifted against the retarding action of the dash-pot, whilst resetting takes place rapidly. The chief disadvantage of this type of relay is the indefinite time delay and trouble in service. The setting varies with the ambient temperature and the alteration of the viscosity of the retarding medium. The wear of the plunger of air-dashpots will also have a considerable effect. The relay, however, is very simple and still used where no special accuracy of timing is required.

Another means of delaying the action of a switch is the use of wind-friction. The plunger of the operating solenoid carries a tooth-rack, which, when lifted, engages and drives a highly-geared mechanism coupled to a fan or wind-wheel, the rotation of which will absorb energy and thus delay the movement of the plunger. To allow quick resetting, a free-wheel motion is incorporated.

Instead of using wind friction, an eddy-current braking device can be coupled to the rack and pinion drive, consisting of a copper or aluminium disc, rotating between the poles of a permanent or electro-magnet. By the rotation of the disc in the magnetic field, eddy-currents will be generated which will produce a braking effect.

If high ratios are employed in gear train mechanisms the friction alone will provide sufficient resistance against the movement of the rack. These kinds of relays are used for comparatively short time delays only (up to about one minute). Instead of the solenoid, a clapper-type magnet can be used, operating the tooth-rack *via* a lever system. Extension or compression springs are used, permitting the relay armature to close completely, storing energy in the spring which is then used to move the rack. By raising or lowering the delay mechanism relatively to the plunger, the length of tooth rack in engagement with the pinion can be adjusted, and this is one method for varying the time delay. These types of delay mechanism are generally provided with an escapement action. As soon as the rack disengages the pinion or the plunger leaves the retarding-medium in the dash-pot, the spring will lift a striker with a jerk to the top position and thus provide a quick action for the operation of the control switch.

The type of relay provided with the gear mechanism gives very accurate timing, but is complicated and subject to excessive wear by too frequent operation.

All the relay types described above, are "reversible," *i.e.*, they can also be used to delay the operation of a switch when the relay coil is de-energised. Such relays are frequently used in conjunction with no-volt relays to prevent a starter from being tripped, due to transient failures of the mains. It will only be tripped should the duration of the fault exceed a certain time.

For certain delaying actions, *e.g.*, accelerating of motors, the delaying mechanism can be suitably coupled to the contactor

armature and operated by the latter. The relay then takes the form of a special auxiliary switch. However, this combination of contactor and delaying device is only possible if the contactor magnet is strong enough to provide the extra pull.

Another type of relay uses the effect of heat on a bi-metal strip, or an extension rod or a sealed container, filled with a medium with a high temperature expansion coefficient. The heat is applied either by allowing a heavy current to pass directly through the trip mechanism or by using a separate heating element, and the time required to complete a certain movement, which in the end causes a switch to operate, is used for the delay. The disadvantage of this class of relay is the comparatively long time it requires for resetting and the inaccurate time setting which depends on ambient temperature and mains voltage (which is responsible for the heating effect). They are classified as thermal time-delay relays.

A special time-delayed relay for D.C. use only is the "induction" or "slugged" relay. According to the rule of Lenz, any alteration (electric or magnetic) in an inductive circuit will cause the flow of a current opposing this alteration (self-inductance). A relay, closing or opening, constitutes a magnetic circuit in which an alteration is taking place. If a special low-resistance short-circuited winding is wound around the core, any alteration of the magnetic circuit will cause an induced voltage in this winding, with a consequent current flow, opposing the action of the relay. The same will happen if the relay coil is energised or de-energised ; in both cases, currents will flow in the short-circuited winding. According to the time constant of this winding, these currents will require a certain time to die down and thus delay the opening or closing of the relay. The maximum delay which can be achieved in this way is about 5 seconds. By suitable arrangement of the short-circuited winding, it is possible to produce either a closing or opening delay, so that the time delay is only active during one operation.

For very long time delays clock-type relays are in use, consisting of a clockwork mechanism which operates one or more contacts to make or break at pre-set intervals. Relays of this type are usually called "time switches" or process timers, and are chiefly used to control repetitive processes (sucking and blowing of ventilators, forward and reverse movement of a conveyor, etc.).

For frequent and repeated timing operations pilot motor-driven timing devices may also be used. The pilot-motor is coupled to a camshaft *via* a reduction gear, the switches being operated by adjustable cams. Only limited time adjustment is possible, and to increase the range speed variation of the pilot motor is resorted to. One of the most common methods is to mount an eddy-current brake disc on the fast-running shaft of the series wound pilot motor and to use either permanent or electro-magnets to produce a braking effect. By varying the current or the position of the

braking magnet, the effect can be controlled. Such pilot-motor-driven mechanisms can operate any required number of switches. (For example, see Fig. 4).

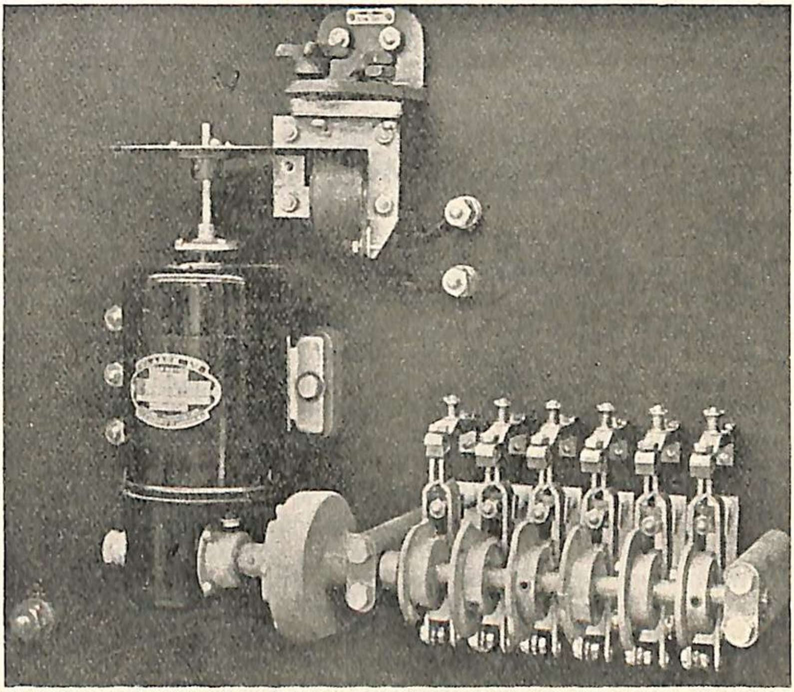


Fig. 4—Pilot-motor-driven Master-Controller, with Cam-operated Switches and Eddy-Current Braking of the Motor Shaft.

(6) Protective Devices.

These are required to protect the motor against damage due to overload, phase-failure, excess voltage, excess speed, etc. The most important of these protective devices is the overload relay, or, to be more exact, the excess current relay.

Overload Relays.

These are a standard feature of every starter. Different types of overload relays are in use.

The electro-magnetic overload relay consists of a solenoid, the plunger of which is prevented from being pulled up immediately by oil or air dash-pots, gear mechanisms, or other means. The higher the current in the solenoid windings, the stronger the pull

and, therefore, the shorter the time required to lift the plunger and operate the trip switch. This produces a certain inverse time/current tripping characteristic which can be adjusted to suit the temperature/time curve of the motor. A heavy overcurrent will cause a rapid temperature increase and requires a short tripping time and *vice versa*. Very heavy excess currents, like short-circuit currents, effect practically instantaneous tripping, whilst very slight over-currents of about 5 to 10 per cent. in excess of the normal current, which could affect the motor insulation after a while, might not cause the overload relays to trip at all. One of the chief troubles of most overload relays of this type is that such slight excess currents can only be dealt with effectively with "light setting," when ordinary current peaks, *e.g.*, starting peaks, may cause the overload relay to trip. This can be overcome by providing, *e.g.*, two overload relays, one with a light setting and one with a heavier setting. The lightly-set relay is short-circuited during starting by a separate contactor to prevent it from tripping and the other relay has to protect the motor during that time. After completion of the starting process, the first overload relay is inserted in the circuit and takes over the protection of the motor during running. This method gives satisfactory results, but is complicated.

A different principle is used for the thermal overload relay. The motor current heats up an element which should have a similar time/temperature characteristic as the protected motor. The elements used for tripping are either bi-metal strips, extension rods, solder pots or gas-filled containers. The bi-metal strip and the extension rod and gas-filled container will be subjected to a deflection depending on the heat administered whilst the solder-pot type will free a tripping element inside the pot by melting some alloy. The heating can be direct by using the tripping element as a current-carrying part or by separate heating elements.

The chief advantage of the thermal overload relay is the good tripping results obtainable at low overloads. However, heavy excess currents are not dealt with instantaneously on account of the inherent delay of the heating elements, which require a certain minimum time to reach a deflection which will trip a switch. This may lead to a damage or destruction of motor and/or relay.

Economy by saving copper and iron in modern A.C. motor design, has caused an increase in the current and flux densities and due to this the starting currents have increased too. In order to avoid the use of two overload relays with different settings, as described above, saturated choke coils can be connected in parallel to the relay or a saturated current transformer can be used to energise it. This does not affect the working of the relay under ordinary circumstances, but the heavy starting peaks will have a reduced effect on the relay. This method works very well with

thermal overload relays, but solenoid relays require special considerations, since the upward movement of the plunger alters the magnetic condition of the relay and thus the flux (and magnetising current). Oil dash-pot relays can be fitted with double or triple acting dash-pot pistons to prevent tripping during starting.

A very useful combination is a thermal overload with a heavily-set solenoid overload. Addition of main fuses (delayed acting, normal or high-rupturing capacity fuses) may be advisable, so that the main contactor need not interrupt heavy fault currents. Fuses alone do not give sufficient protection to the motor, as they cannot guard against long-lasting light overloads and heavy current peaks in the same way as an overload relay.

The trip switches of all protective relays are in the coil circuit and are usually of the normally closed type so that, in tripping, they interrupt this circuit. For latched-in contactors, where it is necessary to energise a tripping coil, normally open contacts are used. Once the starter is tripped, the overload will reset again by allowing the plunger to drop or the thermal element to cool down. The trip switch, however, need not reclose or re-open. It may do so, when "self-reset" overloads are used, but with "hand reset" overloads it is mechanically held in the tripped position by a catch, and only after this has been released by depressing a button, etc., is the switch allowed to reset. This necessitates going up to the starter and performing this resetting operation there. To avoid this, a small resetting coil with a magnet can be used, freeing the trip and permitting the overload switch to reset when being energised through a remote push-button.

Self-reset overloads are used with all kinds of starters where, after tripping, a definite restarting operation by hand (for instance, depression of a button) is required. This will replace the hand-resetting operation. Only starters controlled by automatic devices (float switches, pressure or temperature relays, etc.) require hand reset overloads to prevent "pumping." Should an overload occur, the starter is tripped and with self-reset overloads the control circuit would be remade immediately the overload resets. Since most probably the control switch is still made, this would amount to restarting the motor without removing the cause of the overload, which would again result in tripping of the overload relay. This cycle would continue until a breakdown occurred.

Current Relays.

Current relays are used to provide a certain control over consecutive switching operations, causing peak currents. These relays are of a series type, which pull in at a given maximum current and drop out again after the current has dropped to a lower value.

Phase Failure Relays.

Failure of one phase only in a two or three phase system will not stop a motor from running, and will not necessarily trip the starter, since generally the control circuits are supplied from one phase only, which may have remained sound. Overloading of the motor-windings fed by the sound phases might occur with the overload relays not taking care of such a case, since only the line current passes through them. The line current of delta connected motors under light loads and failure of one phase will not rise substantially above the rated current but circulating currents in the motor windings might cause damage.

Sometimes the failure of one phase would, however, have more serious results than just damaging the motor. In hoist and lift schemes, *e.g.*, when hoisting a heavy load, the motor will not be able to pull the load if single-phasing occurs at that moment and the load will start to descend and drive the motor. Since the motor is energised *via* the top-limit switches only, the reaching of the bottom position will trip the bottom-limit switches, which will have no effect on the control circuit and will not apply the brakes, and serious damage may be caused to the lift or hoist. To guard against such occurrences, special multi-phase relays have been built to trip the control circuit in case of failure of one phase only. In such a case, the balance of the multi-phase system is upset and the trip switch operated.

Minimum Current Relays.

Minimum current or load relays are required to shut-down a starter should the load fall below a certain limit. Minimum current relays are of the same design as excess current relays, minimum load relays (as any other load relay) are based on the inter-action of a current and a voltage coil.

Reverse Current Relays.

Reverse-current relays are sometimes required to check the reverse-flow of electric energy. This kind of relay is also provided with current and voltage coils.

Earth Leakage Protection.

It is possible that, due to a failure of the electrical insulation, external metallic parts may become 'alive.' If the neutral of a three-phase system or one side of a D.C. or single phase A.C. system is earthed, the metallic parts may attain a dangerously high potential above earth and anybody touching these parts will be liable to an electric shock. To prevent this happening, every metallic part of an electrical machine or control unit is solidly earthed. It is

possible that this earthing connection deteriorates or even becomes broken, in which case an insulation fault would not normally be detected.

Two methods are chiefly used to detect faulty insulation. In one case, the leakage current flowing through the faulty insulation to earth can be used to operate a relay. In a three-phase system, this leakage current will cause the three-phase currents to become unbalanced and the out-of-balance current is then utilised for relay operation.

The second method employs a high resistance voltage relay connected between metallic enclosure and earth. If the potential of the casing rises to more than 40 volts above earth potential the relay will trip.

(7) Isolators.

These are required to disconnect the starter from the mains to make maintenance and repair possible. They are not designed to break the load current and special care has to be taken to interlock them in a proper way to guard against this. Interlocks, as described in a previous chapter, are required for this purpose. Generally an auxiliary switch is provided in the coil circuit, arranged on the isolator shaft and designed to break in advance of the main contacts, so that, on opening the isolator, the coil circuit is tripped first and thus the contactor brought out, breaking the circuit. Very often, also, mechanical tripping devices are incorporated, especially in the case of latched-in contactors. A system of levers is arranged in such a way that the catch, holding the contactor closed, is lifted before the isolator opens and the circuit is again interrupted on the contactor.

Auxiliary isolators, consisting of small switches and arranged to be operated from the main switch shaft, are provided to break and isolate all incoming auxiliary circuits (sequence circuits, coil supplies, etc.). This is required to ensure that when the isolator is off, not only is the main supply isolated but also all auxiliary components are dead (see Fig. 11).

The isolator is also usually mechanically interlocked with the cubicle door to prevent the latter being opened with the isolator on.

CHAPTER III.

PRINCIPAL CIRCUITS OF AUTOMATIC SCHEMES.

(1) General Remarks.

Usually difficulties in reading schematic diagrams are experienced by persons not familiar with this kind of representation. This may be explained partly by the fact that although a standard

list of references exist, many diagrams are still to be found which do not comply with these recommendations.

In this booklet a method similar to the one adopted in telephone systems is employed and with a little exercise even very complicated circuits can be read and understood easily.

To facilitate the understanding of the functions of a scheme, the different components are lettered to a system as follows :— a capital letter for any component or instrument in general, small letters with indexes for all the auxiliary parts (coils, switches, etc.). Example :—C for contactor, c_1 for operating coil, c_2 for auxiliary switch.

The symbols and references are those recommended by the B.S.I. handbooks, No. 822—1938, and No. 108—1937, and where new ones were required, the B.S.I. references were used as a guide.

The schematic or key diagram shows all the components of one part (contactor, relay, etc.) not combined in the actual arrangement (as in a wiring diagram), but split up, each part being shown in the appropriate circuit in which it has to function. The above-mentioned lettering system will assist in reading the diagram. All the components are shown in the off position, that is de-energised. The various main and control circuits are kept apart, and for the sake of a simpler diagram, the former have sometimes been shown only as single-line diagrams (see Figs. 31 and 32).

The general tendency is to simplify all circuits as far as possible and to separate the different control circuits. The use of "common feeds" has been abandoned, since these not only make the circuits more complicated for perhaps the sake of an auxiliary switch, but may also endanger the correct working of the scheme by some unforeseen "back-feed," etc. Parallel feeds are dangerous in D.C. circuits, where they might produce either a "slugging effect" or even cause the closing of smaller relays and contactors instead of tripping them. This can happen if two inductive circuits (*e.g.*, shunt-field windings, contactor and relay coils, brake solenoids, etc.) of different proportions are connected in parallel. In opening the circuit, a discharge-path for the self-induced voltage of the larger inductance may be formed through the smaller coil, causing this either to remain closed (instead of being tripped simultaneously) or, in extrene circumstances, if already tripped, to reclose.

Whilst D.C. coils can be safely connected in series, this should not be done with A.C. coils. If the two contactors or relays fail to close simultaneously, the one closing first will, by the increase of its impedance, limit the current flowing in the circuit, and this reduced current may be too low to ensure closing of the second contactor.

The breaking of an inductive D.C. circuit will also cause voltage peaks, due to the self-induced voltage and these might endanger the insulation if a suitable discharge path be not found. This is

usually provided by a resistance, roughly $2\frac{1}{2}$ to 3 times the value of the resistance of the coil, connected in parallel to the latter.

In place of ordinary resisters with straight-line current-voltage characteristics, special non-linear resisters can be employed which will pass very much more current at higher voltage. Thus, at normal voltage the watt consumption of the resistance is low, but when a discharge occurs, the resistance effectively reduces the voltage peak by passing a fairly large current.

A certain amount of "slugging" will occur, due to these discharge resistances.

Schemes should be absolutely fool-proof, so that even seemingly meaningless operations of push buttons or control switches cannot endanger the safety of operator or machine.

(2) Methods of Contactor Control.

The simplest control is an on/off switch, breaking and making the coil circuit of the contactor, which is thus acting as a remotely controlled switch.

A step further is the use of press or push buttons which make or break a circuit only momentarily and reset when the pressure on them is released. As shown in Fig. 5, the coil is energised *via* the stop button through the start button when the latter is depressed. When releasing the start button, the coil would again be de-energised and the contactor would open. To prevent this, auxiliary switch c_2 on the contactor is used. This is a switch open when the contactor is open and, on closing of the latter, will short-circuit the start button and maintain the coil circuit, hence its name, "maintaining switch." To trip the contactor, the stop button has to be depressed, thus interrupting the coil supply. It is important that this stop button in all cases remains master over the start button, so that if depressed, it prevents the contactor from closing, should the start button be depressed simultaneously.

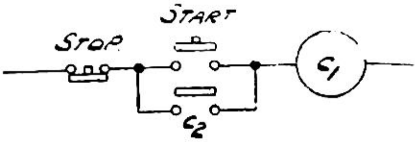


Fig. 5.

An extension of the scheme of Fig. 5 is the use of three push buttons, as shown in Fig. 6—one for "stop," one for "start" and one for "inch" or "jog." The latter means the contactor will close only as long as the respective button is depressed, and no maintaining takes place. This can be done by special double-pole push buttons, but it is usual to employ an auxiliary relay CR, as shown in the diagram. On closing the inch button, c_1 is energised only

and tripped again when this button is released. When depressing the start button, the relay coil cr_1 is energised and maintains itself by means of switch cr_2. The normally open switch cr_2 is also closed and energises c_1, closing the contactor. Again, the stop button is master.

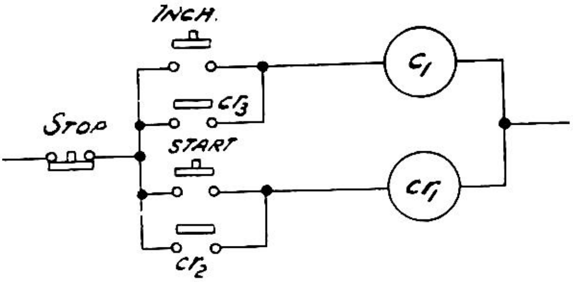


Fig. 6.

Very often it is desired to make use of a float switch, pressure switch, etc., to stop and start a motor. This switch will act in the same way as an on/off switch, but it is usual to provide a three-position switch on the starter with an extra off-position, to be able to start and stop the motor for test purposes by hand, independently of the position of the control switch. Fig. 7 shows a scheme of this kind.

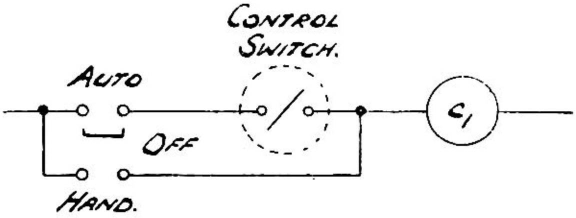


Fig. 7.

Sometimes it is found necessary to start and stop a motor in connection with the rise and fall of pressure, temperature, water-level, etc., and the means of control are usually fairly delicate instruments which cannot deal with the closing or opening current of a contactor. A double-pole relay is interposed in this case, as shown in Fig. 8. The instrument is usually provided with two contacts, one for starting and one for stopping, both closed when the appropriate values of the controlled medium are reached. In closing the start contact, a circuit is made, energising cr_1, causing cr_2 and cr_3 to close. Switch cr_2 maintains cr_1 in parallel with the starting contacts of the instrument and cr_3 energises c_1. The pressure or temperature rises and the start contacts open. When

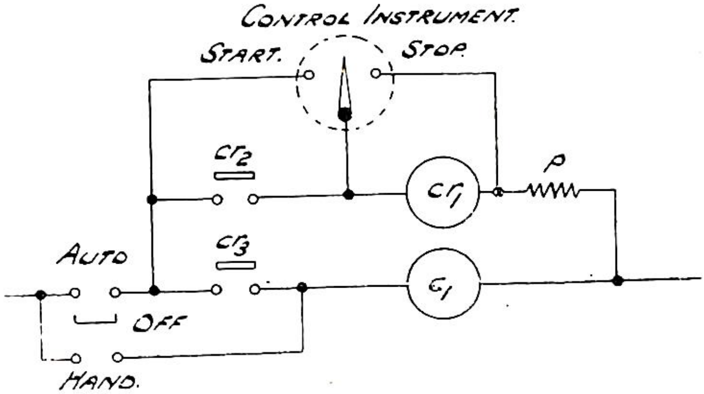


Fig. 8.

reaching the final value, at which the motor has to be stopped, the "stop" contact is closed and since this is in parallel with coil cr_1, this is short-circuited and consequently the relay will drop out and also de-energise c_1. To limit the short-circuit current to a reasonable value, resistance p is inserted.

Again, a three-position "auto-off-hand" switch is incorporated.

Other control gear may be used, instead of push buttons, *e.g.*, joy-stick controllers, drum switches, etc. Due to the required service (rolling mill controls, etc.) they are sometimes of very heavy design, despite the fact that they have to deal only with control circuits. These switches make the selected circuits in the various positions and act as on-off switches for the individual coil circuits. These switches make the selected circuits in the various positions and act as on-off switches for the individual coil circuits.

They are also often fitted with no-volt contacts which are made during operation of the switch only, acting in the same way as a start button. When the switch is released, these contacts break, the respective contactor maintaining itself through its maintaining switch. Should a mains failure occur, the contactor will drop out and cannot re-close until the switch has been operated again.

(3) Interlocking Circuits.

These can be grouped in various classes :—

(*a*) to prevent one contactor from closing when another contactor is closed ;

(*b*) to trip one contactor if another contactor is tripped ;

(*c*) to ensure a certain definite order of closing and/or tripping ;

(*d*) door and isolator interlocks, etc.

The first-mentioned kind of interlock is usually provided in the case of reversing contactors or any other pair of contactors, which must not close together (see Figs. 18 to 23). Fig. 9 shows

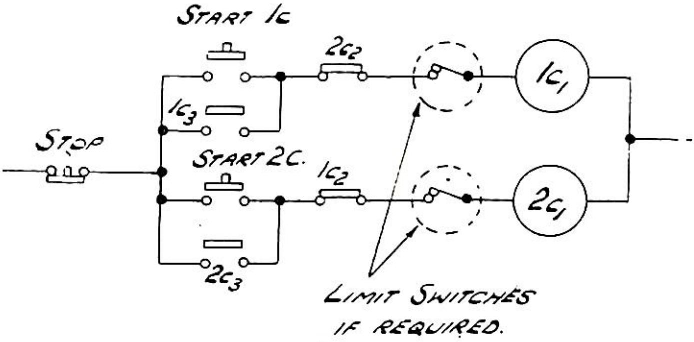


Fig. 9.

the principal scheme. If $1c_1$ is energised $1c_2$, which is normally closed, opens and makes it impossible to energise $2c_1$, and close 2C. Switches $1c_3$ and $2c_3$ maintain the respective coil circuits as before.

Any external limit-switches, etc., which have to stop the motor after a certain position is reached, will have to go in series with $1c_2$ and $2c_2$ as required.

Sometimes it is desired to energise two or more contactors at the same time and, should one fall out, the others should drop out too. To ensure this, the maintaining of one is done by an auxiliary switch on the other contactor, as shown in Fig. 10a. This scheme also prevents back or parallel feeds, which is especially important in D.C. systems. It is simpler to maintain only the more important contactor and have the other either in series (in case of D.C.) or in parallel (in case of A.C.), but should 2C fail, nothing would happen to 1C, as shown in Fig. 10b. Such a scheme is, therefore, not applicable to every case.

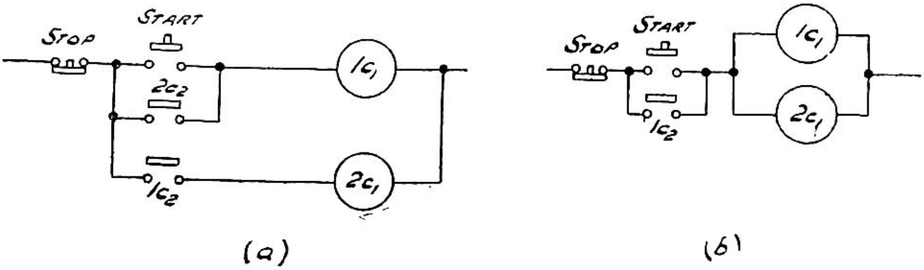


Fig. 10.

When a definite order of starting of a number of motors is required, "sequence interlocking" is resorted to. In this case, the following starter is controlled by a normally open switch on the preceding one, and it is customary to provide a hand-operated paralleling switch for emergency starting and stopping. Fig. 11 shows such a scheme. 1C closing will maintain itself in the ordinary way and also prepare the circuit for $2c_1$ which now can close. This scheme can be continued for any number of starters. One starter in the sequence shutting down will also force the starters, following in the sequence, to close down. This does not affect the starters preceding the one which closed down and which continue to remain closed.

If the various starters thus interlocked are housed in different cubicles, it is advisable to provide special isolators for the switches $1c_3$, $2c_3$, etc., to make sure that these are also dead when the rest of the starter is isolated. These auxiliary isolators IS_2 are shown in Fig. 11.

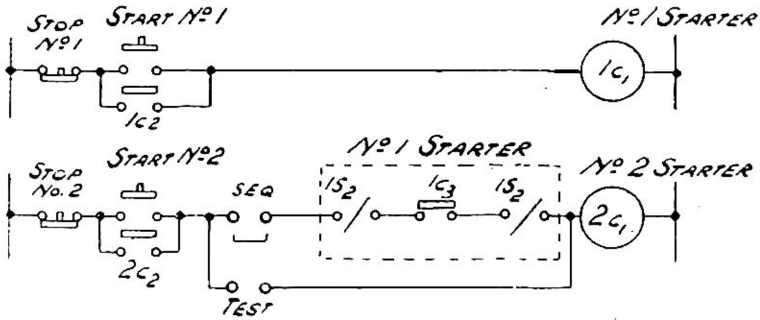


Fig. 11.

In the case of resistance starters, switch c_3 is usually fitted on the final starting contactor to make sure that the motor has reached full speed and the starting process is completed before the next motor is allowed to start.

The last-mentioned group of interlocks (*d*) are those to ensure either the full isolation of the starter with the cubicle doors open or the interruption of the main circuit by the contactor and not by the isolator or other switches. The first is achieved by an auxiliary switch held closed by the door and opened when the door is opened, thus tripping the contactor. The second result is achieved by an auxiliary switch on the isolator or switch with which it is desired to interlock the contactor. This switch is arranged to break in advance of the main contacts and so bring out the contactor. (See Isolators).

To prevent the operation of switches under full-load, it is sometimes advantageous to use a locking coil, which will in the closed

position of the switch lift a plunger into a recess in a cam fixed to the shaft and prevent operation of the switch as long as the coil is energised. This scheme is often used in connection with reversing switches.

A different group of interlocks are the "start-interlocks." These consist of auxiliary switches on various components (time switches, master controllers, resistance contactors, shunt regulators, etc.) closed only in the position required for starting and connected in the initial starting circuit. As Fig. 12 shows, the contactor coil

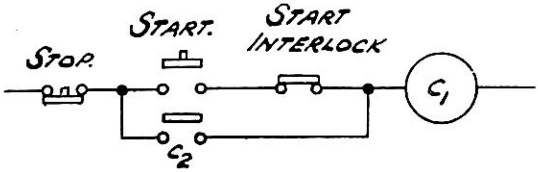


Fig. 12.

is energised *via* these switches, thus testing the position of the component, and finally maintained across the switch, so that, once the contactor has closed, the regulator, etc., can be moved from the starting position.

(4) Pilot-Lamp Circuits.

Pilot-lamps should, if possible, be fused always on both sides by separate fuses, if connected across two lines. One fuse will be sufficient where the lamp is fed from line and neutral. These circuits are more liable to faults than any other and common control and pilot-lamp fuses would cause the starter to trip every time a fault developed in the lamp circuit.

If possible, separate auxiliary switches should be used to control the lamps. Either series resistances, or in case of A.C., series condensers are used to reduce the supply voltage to one of the standard lamp voltages. It is an advantage to use a lamp voltage slightly below the rated voltage. Brilliance is not materially affected, but the life of the lamp is greatly increased. (For example, see Fig. 16).

(5) Pilot-Motor Drives.

Pilot motors may be of the A.C. or D.C. type and are used for reversing or non-reversing duty, with or without dynamic or plug braking. They are used for regulator drives, for master-controllers, cam-operated switch arrangements, etc.

The motors are often of the universal type for use on D.C. and A.C., but in the latter case also, reversing single-phase induction motors may be employed. Series motors for reversing duty are

usually provided with two field windings, one for forward and one for reverse rotation, but single-field types with armature reversing are also used occasionally.

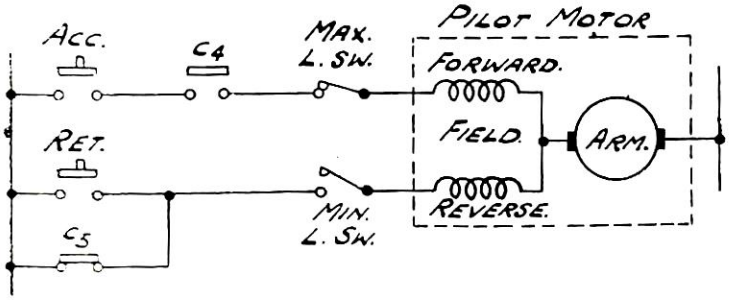


Fig. 13.

A simple example is set out in Fig. 13. Switches c_4 and c_5 are on the main contactor. After this has closed, c_4 has prepared the circuit for the forward field winding of the pilot-motor. On depressing the accelerating button, the motor is energised and drives the regulator, etc., in the required direction until the button is released or the maximum position is reached, when the limit switch will open and stop the motor. To slow down, the retard button has to be depressed so that the reverse field winding is energised *via* the minimum limit switch, which opens only in the minimum position (slow-speed). It closes immediately after the regulator brush has left this position, and it also serves to stop the pilot-motor when resetting after the main contactor has tripped. In this case, switch c_5, which is normally closed, will energise the motor, bridging the retard button.

(6) Control Systems for Resistance Starters.

Two distinct types of start control systems are in use, time-control and current-control. Sometimes also a combined time-current-control is employed.

Time-control can be effected by any of the time-delaying devices described before and is used for resistance starters, star-delta starters and auto-transformer starters. Also, multi-speed change-pole motor starters and supply change-over schemes make use of this type of control. Its chief feature is a definite starting time delay regardless of the starting torque, which may cause severe current peaks if set too short, but prevents burning-out of starting resistances. With varying starting loads it is impossible to achieve correct timing for the best acceleration and an average timing is generally aimed at. Failure of any time relay in the series may cause the burning-out of the following starting resistance steps, since none of the time relays controlling the respective re-

sistance contactors would be energised and no closing of the latter would take place. Such occurrences, however, can be avoided by using a pilot-motor-driven master-controller where all resistance contactors are controlled by cam-operated switches and the failure of one switch or contactor would not prevent the remaining contactors and switches from operating. The only possible failure, which would also in this case cause the burning-out of the starting resistances, would be a break-down of the pilot-motor or cam drive during the starting process. A thermal relay in parallel to the last step of the starting resistance, which interrupts the coil supply of the main contactor, if energised too long, is a protection against such an occurrence. This relay would operate after a definite delay and thus prevent the overheating of the resistance. A similar method is adopted for the protection of a starting auto-transformer in Fig. 27.

Current control can be effected by various methods. One uses a current relay, combined with the resistance contactor, which shortens the starting step. Such a scheme is shown in parts in Fig. 14. After closing of the first resistance contactor 1SC, the relay coil $1sc_2$ will cause a delay in the operation of the switch $1sc_3$ controlling the shunt closing coil $2sc_1$ of the following resistance contactor. The relay plunger is held up mechanically with the contactor armature in the open position and after closing the action of the current only will hold it up. It will drop after the starting current has dropped to a pre-set value and, in dropping, the contacts controlling the shunt closing coil of the following contactor will close.

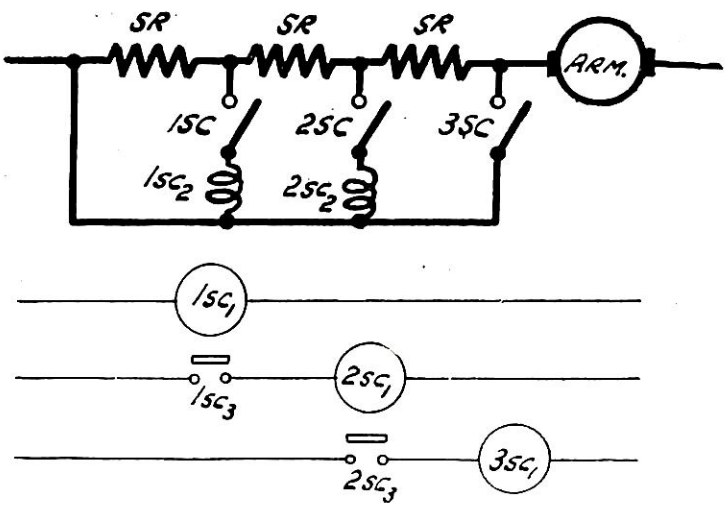


Fig. 14.

This scheme is used for the acceleration of A.C. and D.C. motors.

Another method makes use of lock-out contactors. Part of such a scheme is shown in Fig. 15. The contactors SC are provided with shunt closing coils sc_1 and opposing series coils sc_2. The shunt coils are energised, but the series coils prevent the contactor from closing until the current has dropped to a certain value, when the shunt coil is strong enough to pull in. The chief drawback of this scheme lies in the fact that it is difficult to fix the closing point to a certain current value, since the temperature of the shunt coil controls the resistance of this coil and thus the current flowing through it. With this varying, the pull of the contactor is also varying, and thus the timing. A heavy voltage drop in the mains during starting may prevent the contactor from closing, due to insufficient pull of shunt coil sc_1 and may cause burning-out of the starting resistance.

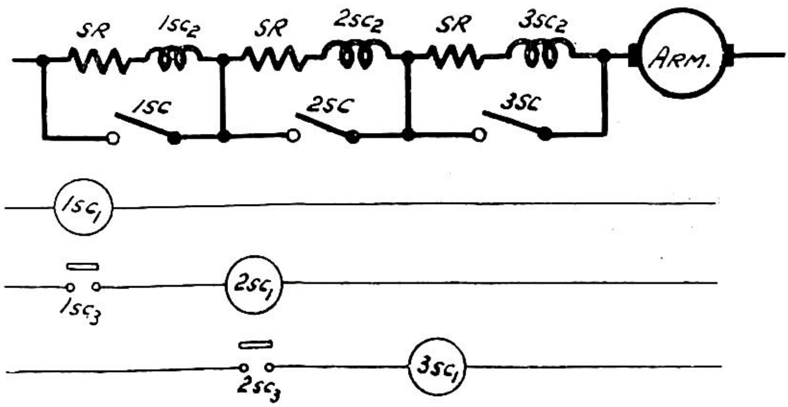


Fig. 15.

The series coils have to be shorted after the contactors have closed, otherwise severe peak currents might cause the contactor to be thrown open.

Series lock-out contactors are also in use employing the saturation of a magnetic circuit at high currents.

Chief features :—Good acceleration of the motor in the least possible time with no undue current peaks. With light loads, rapid acceleration and *vice versa*. Drawback—too heavy starting loads may prevent the motor from accelerating, the current peak will not subside and the contactor may not close, causing the starting resistances to burn out.

Very often a combination of time and current-control is used, cutting out the disadvantages of each. Current relays are employed in connection with pilot-motors driving the controllers and this motor is slowed down by the relay should the current rise to

too high values, and it is only permitted to speed up again after the peak has died down and the relay has dropped out.

Another method makes use of a current-controlled delaying device in combination with pilot-motor-driven controllers or other automatic starter types (solenoid operated auto-starters, etc.). A very suitable device for such a control is the eddy-current brake. A metal disc is fixed to the pilot-motor shaft or is driven *via* rack and gear-wheel from the solenoid plunger of the automatic starter and the magnet providing the braking field is energised by the starting current (or the voltage drop across the starting resistance). Heavy starting currents will cause a more severe braking effect, with a consequent slower starting speed. Figs. 27, 31, 38 and 45 include such schemes.

CHAPTER IV.—AUTOMATIC A.C. STARTERS.

(1) Straight-On Starting.

Straight-on starting is the simplest method for starting induction motors with short-circuited rotor. The starter usually consists of contactor, overload relay and isolator. A scheme of this kind is shown in Fig. 16. The control scheme is simple and straightforward and includes all the features mentioned in previous paragraphs. Start-stop push-button control is shown, control fuses are incorporated, the isolator interlock is_1 and the overload trip switch *ol* are in series with the stop-button, so that either of these on opening will

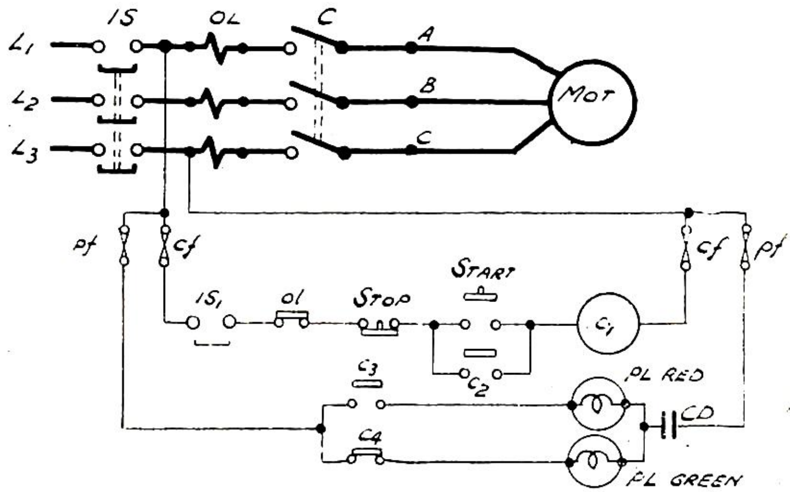


Fig. 16.

trip the main contactor coil circuit. Instead of the push-button control any of the other kinds of control mentioned above could be employed. The diagram also shows the control circuit for two pilot-lamps, one to indicate that the starter is "off" and therefore the motor is at stand-still (green), and the other to indicate that the starter is "on" and the motor is running (red). Two auxiliary switches on the main contactor are used for the control of these two lamps. Two separate pilot-lamp fuses are used and only one common series condenser, since the two lamps will never be on at the same time.

If external limit switches are required to stop the motor, these too will go in series with the stop button. Sometimes it may be necessary to stop the motor by a limit switch, but in order to make some adjustments to the machine it may be required to inch the motor further. In such a case, the open limit switch would prevent this operation. To overcome this, the limit switch is connected in series with the maintaining switch c_2 so that depressing of the start-button will bridge it. Such a scheme is shown in Fig. 17.

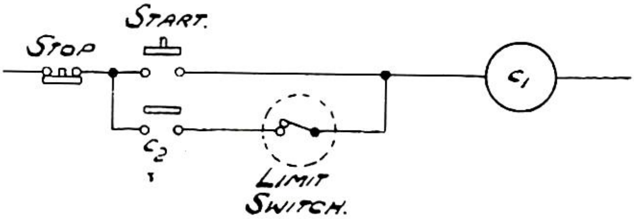


Fig. 17.

The reversing straight-on starter is shown in Fig. 18. The two reversing contactors are mechanically and/or electrically interlocked to prevent simultaneous closing, which would constitute a short-circuit of the mains. The diagram in Fig. 18 shows automatic reversing features controlled by a limit switch on the machine. In the end positions of each travel this control switch will change-over, thus interrupting the coil supply of one contactor and energising the other contactor. Reverse-current braking will take place, followed by rapid acceleration of the motor in the new direction. This scheme is employed very often in connection with reciprocating movements on machine tools (table-feeds, spindles, etc.). No maintaining switches are required, since the control switch remains closed during the whole period of operation. To stop the motor, the on/off switch in the starter has to be put in the off position. The overload trip switch is of the hand-reset type.

If push-button control is required, a scheme similar to the one shown in Fig. 9 has to be incorporated.

Instead of a switch operated by the machine to reverse the motor, time-control element may be used. Such starters are often used

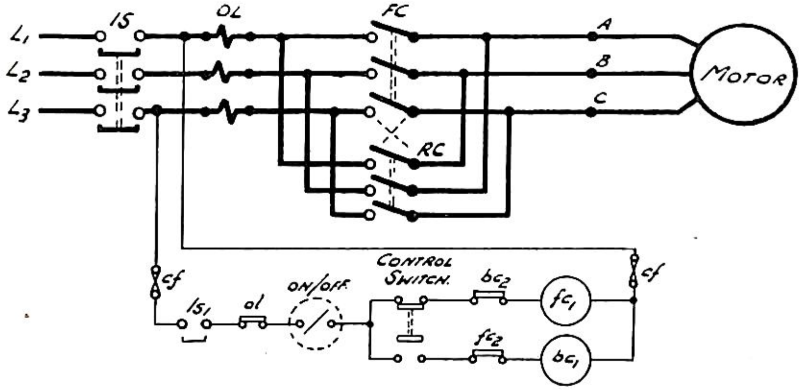


Fig. 18.

to control, *e.g.*, ventilators for sucking and blowing or reversing conveyors, etc. A scheme is shown in Fig. 19, which uses a pilot-motor-driven controller. By depressing a start-button, a control relay CR is energised and maintained *via* switch cr_2. This relay serves two purposes. It acts as a no-volt relay to shut down the starter in case of failure of supply thus preventing a restart. It also completes the necessary auxiliary circuits for the control of the pilot-motor and the contactor coil circuits. By closing cr_4, the pilot-motor, which is of the non-reversible type, will start and according to which switch mc_1 or mc_2 is made, either fc_1 and rc_1 is energised *via* cr_3. Again, cross interlock contacts fc_3 and rc_3 are incorporated apart from a mechanical interlock. After a set time interval one switch will break and trip the respective contactor, and the other control switch will make and energise the reverse

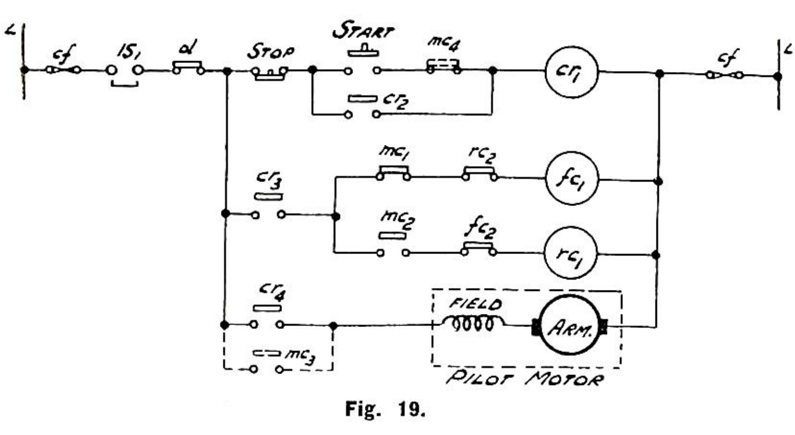


Fig. 19.

contactor. This cycle is continued until the stop-button is depressed and CR is tripped.

It may be desired to restart always at the same point of the cycle. If so, the pilot-motor will have to continue to run after the starter has tripped, so that the master-controller may reach the position required for restarting. A limit switch mc_3, which is only open in this critical position, bridges cr_4 and continues to energise the pilot-motor until tripped when the master-controller has reached the required point. To prevent restarting before the controller is in the desired position, a start interlock switch on the master-controller is included in the starting circuit in series with the start button. This switch, mc_4, is closed only in the start position and only then is the circuit complete for energising of cr_1. As soon as the controller leaves this position mc_4 opens again, but since it is bridged by cr_2, the circuit for cr_1 is maintained. Switch mc_4 and the circuit for mc_3 are shown dotted in Fig. 19. Since the tripping of the starter by an overload requires restarting by depressing the start-button, the overload trip can be of the self-reset type.

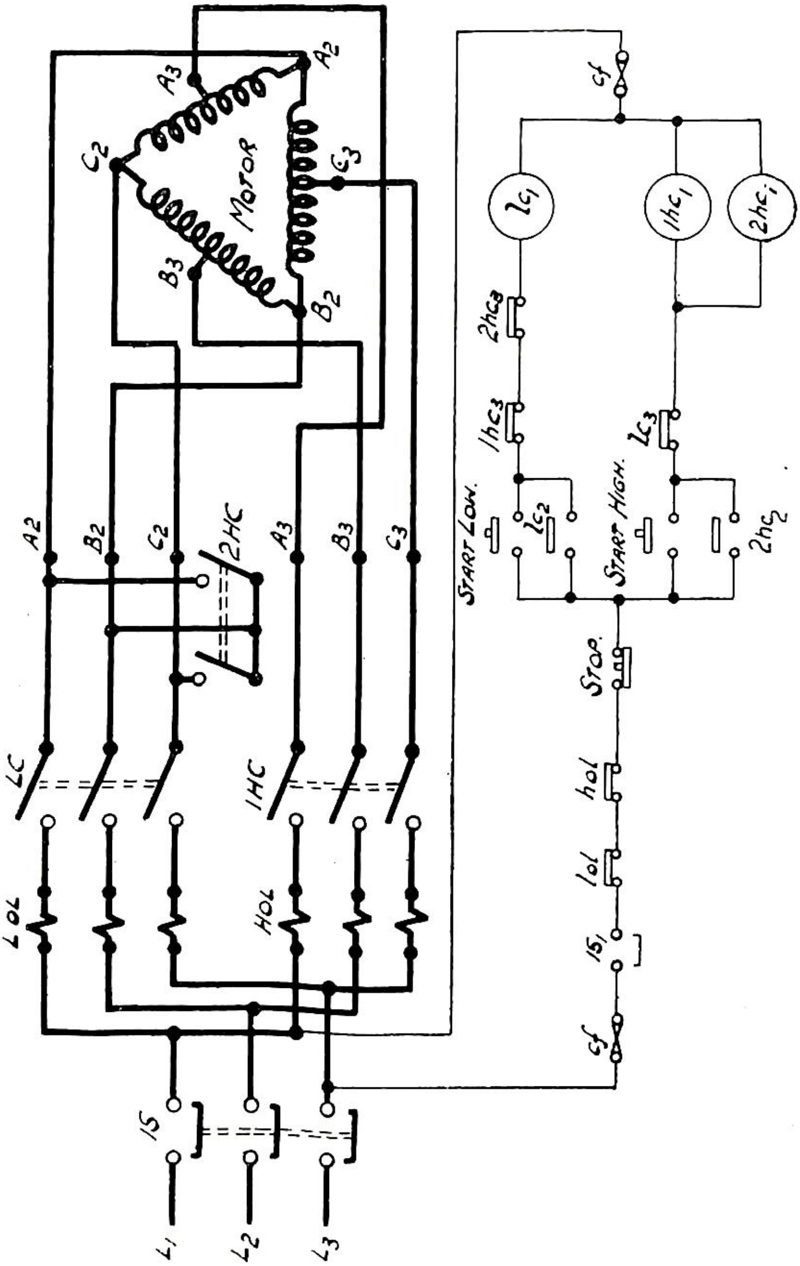
Straight-on starters are also used for the control of pole-changing motors. These may be of the two, three or four-speed type and may either have tapped windings (change-pole windings) or separate windings for each speed.

Change-pole windings generally require the motor windings to be connected in delta for low speed and in star for high speed. This necessitates the provision of a star point which makes the use of two contactors necessary for high-speed running.

Fig. 20 shows the control scheme for a two-speed motor with change-pole windings. The motor may be either of the constant torque or of the constant horse-power type. In the former case the full-load currents for the various speeds will differ and it is therefore necessary to provide two sets of overload relays, one for low-speed and one for high-speed, so that accurate protection is ensured in both cases. Where constant horse-power motors are used (obtainable only with two separate windings) one overload relay will be sufficient.

The two overload trips are in series with the stop button and electrical and mechanical interlocks are provided between the low-speed and the two high-speed contactors. The high-speed control-circuit is maintained by one switch on 2HC only, since failure to close 1HC would not result in any damage to the motor, the latter only failing to start.

Both speeds can be selected by depressing the appropriate start-buttons, and before changing speed the stop-button has to be depressed. It is dangerous to change speed too quickly (see Chapter I.), especially when slowing down from high to low, as a rather severe braking would take place. The motor requires a



A2
A3
C2
C3
B3
B2
MOTOR
2HC
LC
1HC
LOL
HOL
1S
L1
L2
L3
cf
lc1
1hc1
2hc1
2hc3
1hc3
lc3
lc2
2hc2
START LOW.
START HIGH.
STOP.
hol
lol
1S1

Fig. 20.

certain time to reduce its speed and this time delay should be incorporated in an automatic control scheme. This can be done by using special "delayed" push buttons, with a mechanical device, which enforces this delay when changing speed. Included is a trip switch which trips the starter when the delaying device is operated, making the depressing of the stop-button superfluous when changing speed. A further addition is a device to ensure that the "start low-speed" button has to be depressed first, before the "start high-speed" button can be operated, enforcing a certain starting sequence.

This latter interlock, however, can be easily incorporated in the electrical scheme, so simplifying the push-button design. Such buttons can, for instance, be so arranged that the operating pushes do not immediately control the contacts. The latter is done by a separate push arranged underneath the external push, and on depressing the latter, this depression is transmitted to the lower part bearing the contact disc, which then makes or breaks the control circuit.

Between these two pushes a disc is interposed, which has an opening allowing the top part to make contact with the bottom part. Only one such opening is provided in this disc, and since there are two control stations, one for low-speed and one for high-speed, only the one coinciding with the opening in the interposed disc is operative.

This disc can rotate and is driven from a little knob through gearing, so that one part-revolution of the disc requires a number of revolutions of the knob. If, for starting, the disc is in the position where the opening permits the low-speed button to be depressed, the high-speed button is inoperative. After depression of the low-speed button, the control knob will have to be turned several times, until the opening in the disc coincides with the high-speed button, which then becomes operative. In this way, the operator has to spend a certain time turning the knob, thus giving the motor time to accelerate. Immediate depression of the high-speed button does not start the motor, this interlock being part of the electrical scheme, as described below.

If the motor is running in high-speed and it is desired to run it in low-speed, the disc has to be turned back, to allow the operation of the respective button. To prevent the operator turning the disc in preparation for the low-speed running, when running in high-speed, and then leaving it in this position without depressing the button, a little flick-switch is incorporated in the control station, which is operated by the disc, when rotated in the direction from high-speed to low-speed button. It closes a tripping circuit thus tripping the starter and if the low-speed button is not depressed, the motor will stop. This trip switch is inoperative, when rotating the disc in the opposite direction, from low-speed to high-speed. A control station of this type is shown in Fig. 21.

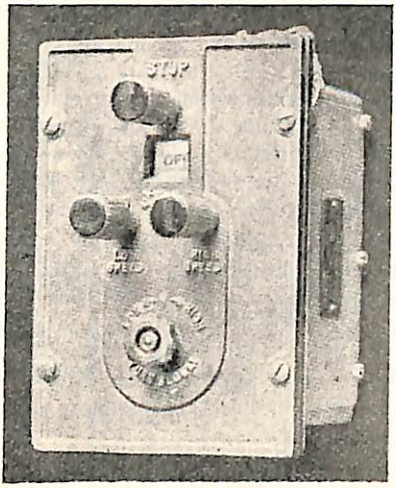
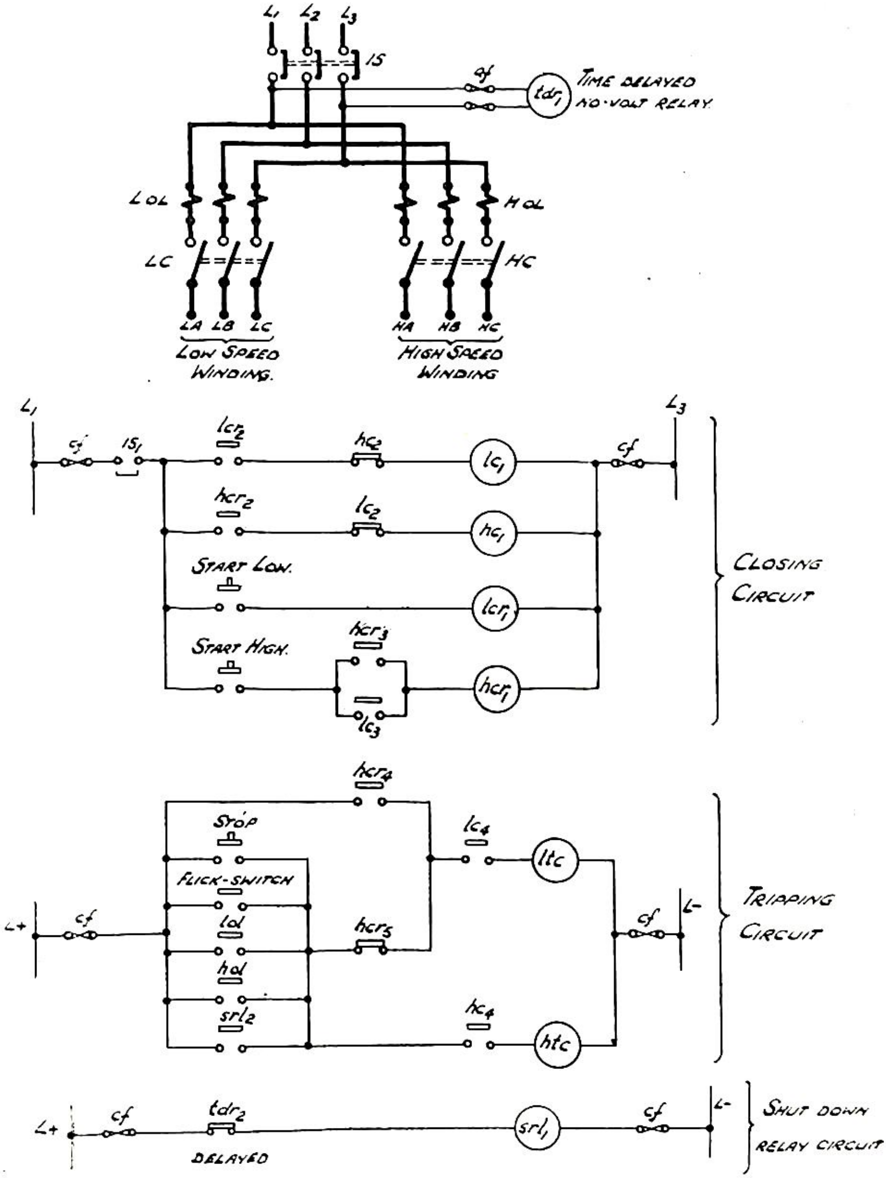


Fig. 21—Push-Button Control Station for Two-Speed Motor Starter, with Delaying Device for Speed Changing and Position Indicator.

The electrical scheme is shown in Fig. 22. Latched-in contactors are used and a separate D.C. supply for the tripping and shut-down relay circuit is assumed. Time-delayed no-volt features are incorporated. The no-volt relay is a time relay with an inverse characteristic, that is, switch tdr_2 will re-close only after a delay when tdr_1 is de-energised or the armature of TDR has dropped out. Switch tdr_2, in closing, will energise the shut-down relay SRL, which in turn energises the tripping circuit of the starter by means of switch srl_2. This relay SRL is only interposed in Fig. 22 to show how a number of starters, fed from the same A.C. supply, can be controlled by one time-delayed no-volt relay. If there is only one starter, switch tdr_2 could directly close the tripping circuit, but if there are a number of starters, relay SRL will be provided with one switch for each starter. This saves a complicated time relay with a number of switches.

In depressing the low-speed button, low-speed control relay LCR is energised and switch lcr_2 closes, energising closing coil lc_1 through interlock switch hc_2. Apart from that, the two contactors LC and HC are also mechanically interlocked. The motor will start up and run in low-speed. Relay LCR is de-energised immediately the low-speed button is released and switch lc_4 on contactor LC is closed, thus preparing the tripping circuit for LC, whilst switch lc_3 prepares the closing circuit for the high-speed control relay HCR.

On depressing the high-speed start button, hcr_1 is energised. Switch hcr_4 closes and energises ltc, thus causing LC to trip. Switch



L1 L2 L3
1S
cf
tdr1
TIME DELAYED
NO-VOLT RELAY.
LOL
HOL
LC
HC
LA LB LC
HA HB HC
LOW SPEED
WINDING.
HIGH SPEED
WINDING
L1
L3
cf
1S1
lcr2
hc2
lc1
hcr2
lc2
hc1
START LOW.
lcr1
START HIGH.
hcr3
hcr1
lc3
CLOSING
CIRCUIT
hcr4
STOP
lc4
ltc
FLICK-SWITCH
L+
lol
hcr5
L-
hol
srl2
hc4
htc
TRIPPING
CIRCUIT
tdr2
srl1
DELAYED
SHUT DOWN
RELAY CIRCUIT

Fig. 22.

lc_3 will open, but the circuit for hcr_1 is maintained by hcr_3. With HCR closed, a circuit is completed for hc_1 via hcr_2 and lc_2 (which will be closed again with LC open) closing the high-speed contactor HC. The tripping circuit for HC will be prepared by switch hc_4. Relay HCR falls off again after release of the high-speed start button and switches hcr_4 and hcr_5 reset. The latter switch is only incorporated to prevent a back-feed to *htc* when HC has closed, but the high-speed start button is still depressed, thus energising HCR. Without switch hcr_5 a circuit would be completed as follows :—L - *cf* - *htc* - hc_4 - hcr_4 - *cf* - L + and HC would drop out again. A continuous closing-and-opening action would commence and switch hcr_5 prevents this.

Turning the knob and disc back from the high-speed to the low-speed button will close the flick switch. This energises *htc* via hc_4, thus tripping the starter and preparing it for a restart by the low-speed button. The stop button or either of the two overload trip switches *lol* or *hol* or switch srl_2 also trip the starter by energising the appropriate trip coil.

It is impossible to start the motor straight into high-speed, since the high-speed relay HCR can only be energised when switch lc_3 is closed.

All the interlocks and start-delays can be achieved also in a purely electrical way, either by the use of a master-controller driven by a pilot-motor or by cam-operated switches instead of contactors, with the cam-shaft driven by an auxiliary motor, or by the use of contactors with interlock and start-delay relays. The latter scheme, however, is fairly complicated and is more liable to trouble on account of the great number of components employed.

Fig. 23 shows a simpler scheme without time delay for the speed-changing operation, but with an enforced starting sequence - low-high. The stop button need not be depressed when changing

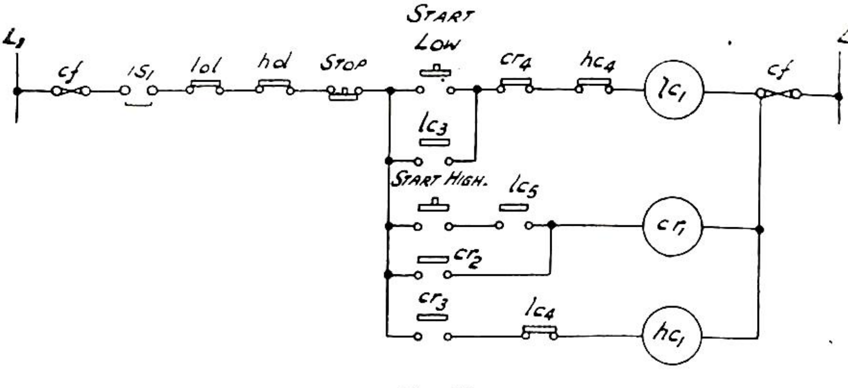


Fig. 23.

from low to high, but in order to ensure a delay when changing from high-speed to low-speed, it will be necessary to depress it and thus trip the starter.

On depressing the low-speed start button, lc_1 is energised through cr_4 and hc_4 and maintains itself by lc_3. Switch lc_5 closes and prepares the circuit for cr_1. When the high-speed button is now depressed, cr_1 is energised and maintains itself by cr_2. Switch cr_4 opens and trips lc_1 which recloses lc_4 so that hc_1 can now be energised via cr_2 and lc_4. The opening of lc_5 has no effect, since cr_2 is bridging it. It is impossible to go straight into high-speed, since the circuit to cr_1 is incomplete with lc_5 open.

(2) Star-Delta, Series-Parallel and Auto-Transformer Starting.

This kind of starting can be applied to any induction motor with short-circuited rotor and also to synchronous motors with short-circuited auxiliary rotor windings (damper windings). The motor is at first connected to a reduced voltage and then, after it has accelerated, to the full supply voltage. Generally three contactors are required for this purpose :—the main contactor, the start contactor and the run contactor. The start contactor, usually of a smaller size, closes first, making the star-point or the series connection or connecting the motor to the tapping on the auto-transformer. The run contactor, closing after the start contactor has been tripped, then connects the motor windings in delta or in parallel or to the full voltage in the case of the auto-transformer starter.

Usually time-control is employed to effect the change-over from start to run, but, especially in the case of big motors, a current relay can be incorporated to prevent changing-over in case the current has not dropped sufficiently. Pure current-control is also possible, the start contactor being provided with a lock-out current relay, controlling the run contactor.

The start-contactor is only required to select the correct starting connections and, after it has closed, the main contactor closes, energising the motor. This sequence is observed with nearly all starters of this kind.

Fig. 24 shows a scheme for a push-button controlled star-delta starter with the time-delay relay TR. This latter can be of any of the types mentioned, tr_1 being the operating coil and tr_2 the switch, opening after a delay (see also Fig. 25).

By depressing the start button tr_1 and st_1 are energised via rn_3 which serves as an electrical interlock with RN. Sometimes an additional mechanical interlock between the two contactors ST and RN is provided. In closing, ST operates the change-over switch st_3, which completes a circuit to c_1 via the still depressed start-button. Switch st_3 also serves as an interlock for RN. Main

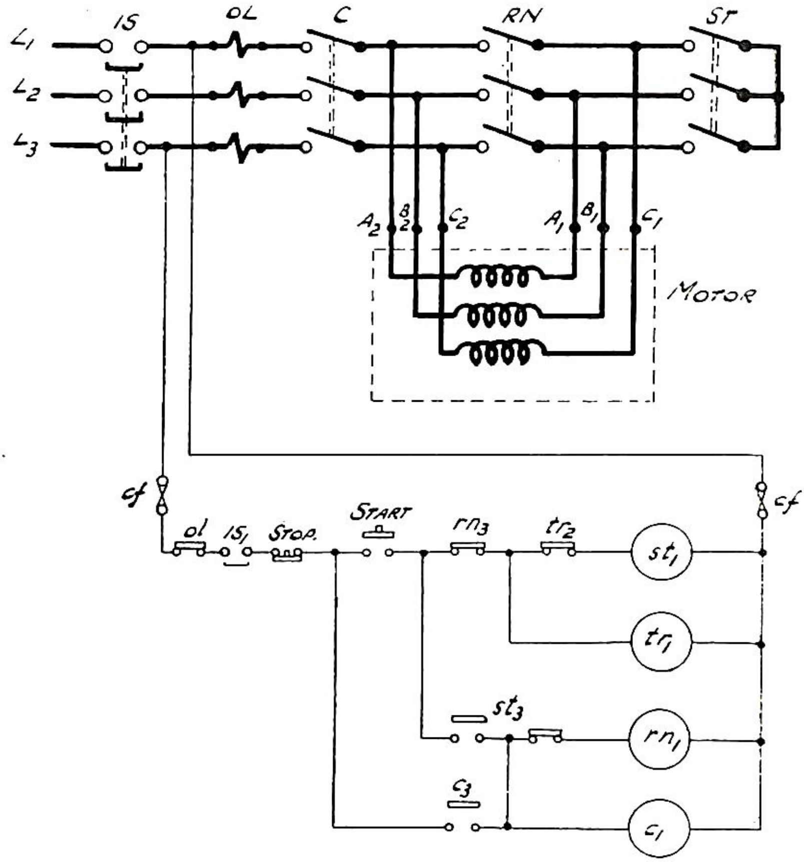


Fig. 24.

contactor C closes and maintains itself by switch c_3 and also keeps st_1 and rn_1 energised via st_3. After a delay, tr_2 will trip and de-energise st_1, tripping ST. Switch st_3 will reset and a circuit to rn_1 is established through c_3 and st_3. RN closes and opens rn_3, de-energising tr_1.

It is important that the start contactor is fully open and no arc remains across its opening contacts, when the run contactor closes, to prevent any short-circuits.

Series parallel starters are similar to star-delta starters, the control circuits being identical. The start contactor is usually of the double-pole type and the run contactor of the four-pole type to change the connection of each half of the phase-windings from series to parallel.

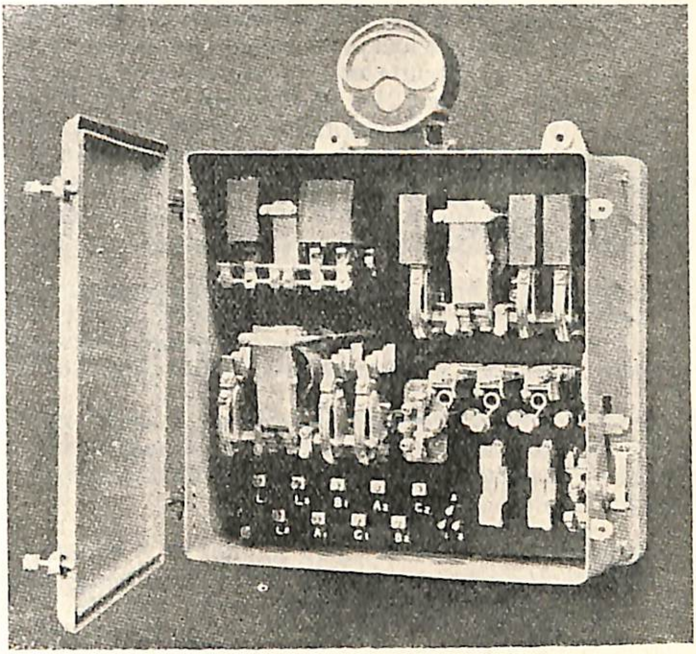


Fig. 25—Star-Delta Starter, with Thermal Overload Relay (T.P.) and Thermal Time Delay Relay, Ammeter, Control Fuses and Auto-Off-Hand Switch.

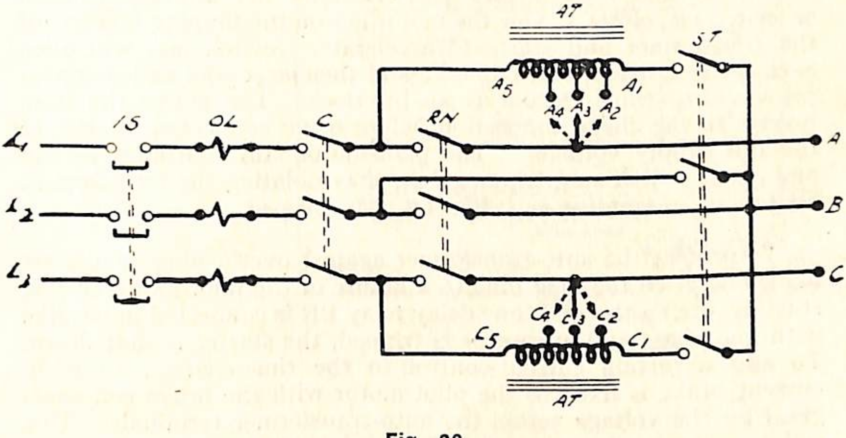


Fig. 26.

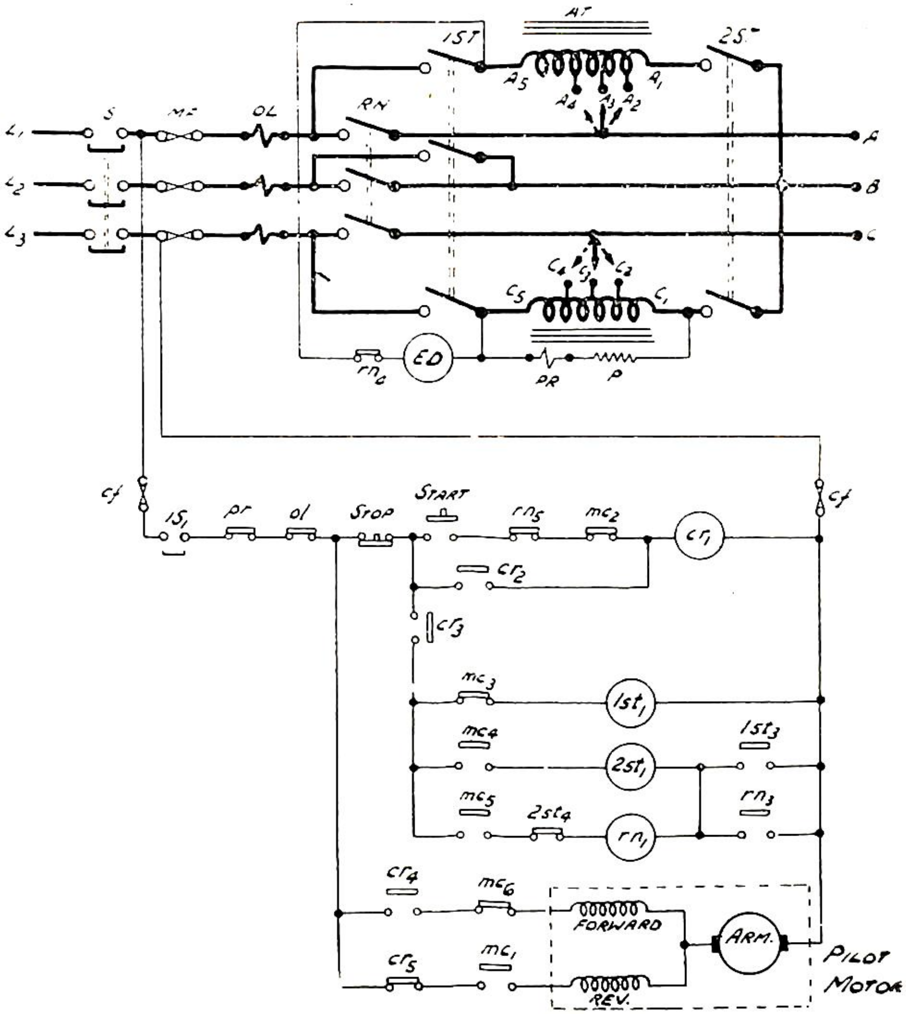
Fig. 26 shows the main connections for an auto-transformer starter. The transformer is of the two-phase type, which, provided the three motor phases are identical, supplies a three-phase starting system. The control circuits of this starter are again identical with the controls of Fig. 24. Start contactor ST closes first, followed by C and this energises the motor via the tapping links which are provided on the starting transformer, to give a variety of starting voltages and thus starting torques. The motor accelerates and after a delay ST is tripped and RN closes connecting the motor to the full supply voltage.

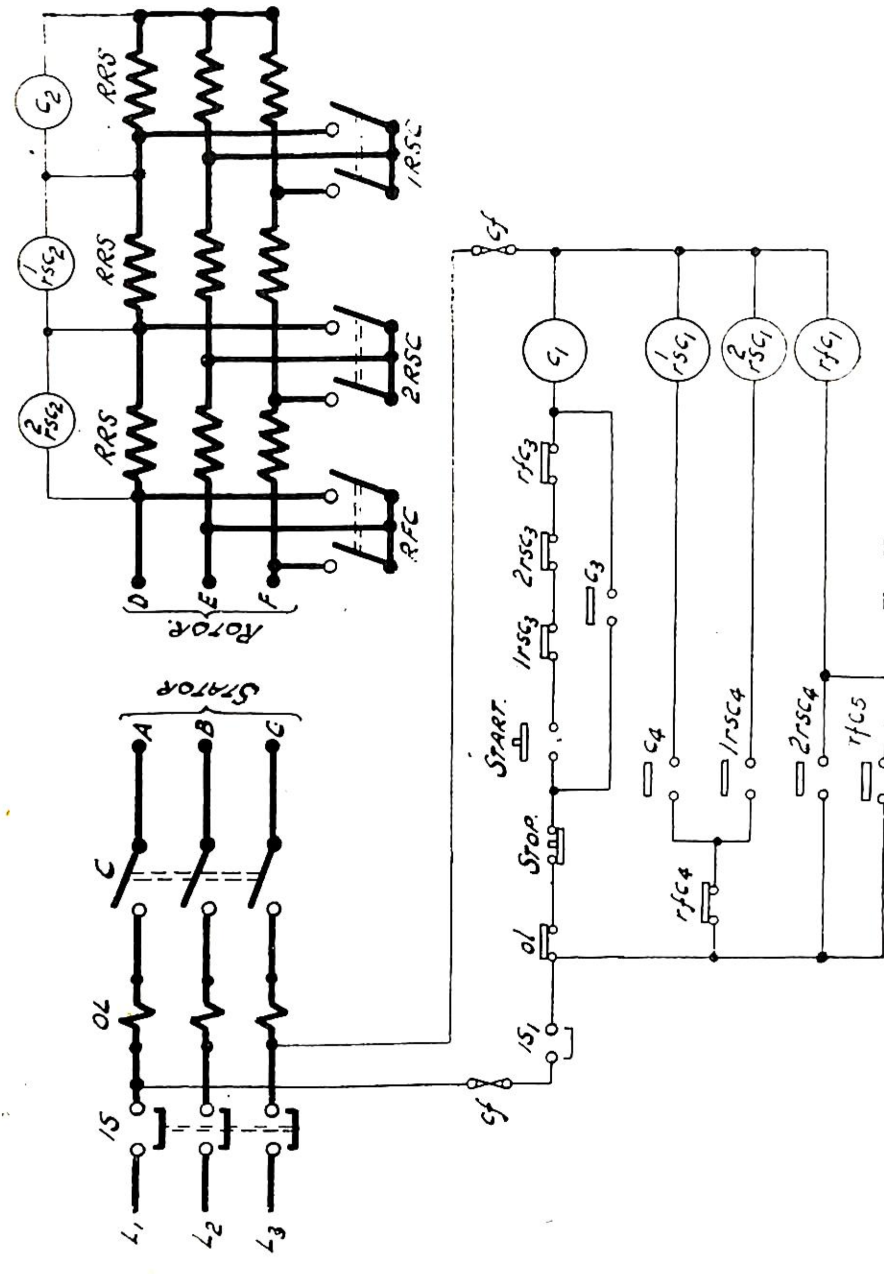
A disadvantage of both star-delta and auto-transformer starting is the interruption of the supply to the stator during changing over. Thus the closing of the delta or running contactor will cause current transients which may have undesirable effects.

To overcome this, resistance change-over schemes have been developed for star-delta starters. For auto-transformer starters "Korndorfer" starting is employed, using the transformer as a choke during change-over.

The Korndorfer method is shown in Fig. 27. Depressing the start button causes control relay CR to close, cr_1 being energised through rn_5 and mc_2, a switch on the master controller which is used for the timing of the starting process. Switch cr_2 maintains CR, and cr_3 and cr_4 closing, energise the pilot-motor driving the master-controller and the first starting contactor 1ST via switch mc_3. Thus the motor is energised with the top portion of the starting transformer in circuit, acting as a choke coil, applying a very reduced voltage. The pilot-motor will start up and with switch $1st_3$ closed, the second start contactor 2ST will close as soon as switch mc_4 closes. Now the motor lies on the tapping voltage of the transformer and starts to accelerate. Switch mc_4 will open again after a delay, and trip 2ST and then mc_5 closes and energises rn_1 via $2st_4$, which serves as an interlock. The motor therefore reverts to the choke connection before being connected by RN to the full supply voltage. The pilot-motor still continues to run and opens switch mc_3, tripping $1st_1$, thus isolating the transformer. Switch rn_3 maintains rn_1 after $1st_3$ has tripped.

To protect the auto-transformer against overloading or against being energised too long (due to a failure of the pilot-motor during starting, etc.) a thermal time delay relay PR is connected in parallel with one phase and in case pr is tripped, the starter is shut down. To add a certain current-control to the time-control, an eddy current brake is fixed to the pilot-motor with the brake coil energised by the voltage across the auto-transformer terminals. This coil, too, is cut out after starting is completed by switch rn_4 opening.


AT
1ST
2S
A5
A4
A3
A2
A1
L1
L2
L3
S
MF
OL
RN
A
B
C
C4
C3
C2
C5
C1
ED
rn6
PR
P
cf
1S1
pr
ol
STOP
START
rn5
mc2
cr1
cr2
cr3
mc3
1st1
mc4
2st1
1st3
mc5
2st4
rn1
rn3
cr4
mc6
FORWARD
ARM.
PILOT MOTOR
cr5
mc1
REV.



C_2
$1\ rsc_2$
$2\ rsc_2$
RRS
RRS
RRS
1RSC
2RSC
RFC
D
E
F
ROTOR.
STATOR
A
B
C
C
OL
1S
L_1
L_2
L_3
cf
cf
$1S_1$
ol
STOP.
START.
$1rsc_3$
$2rsc_3$
rfc_3
C_3
C_1
$1\ rsc_1$
$2\ rsc_1$
rfc_1
C_4
$1rsc_4$
$2rsc_4$
rfc_5
rfc_4

Fig. 28.

(3) Rotor Resistance Starters and Regulators.

Two separate groups of contactors are used in this kind of starter—the stator and the rotor contactors. The latter group may be replaced by a pilot-motor-driven regulator, if speed control is required. Current as well as time-control is used.

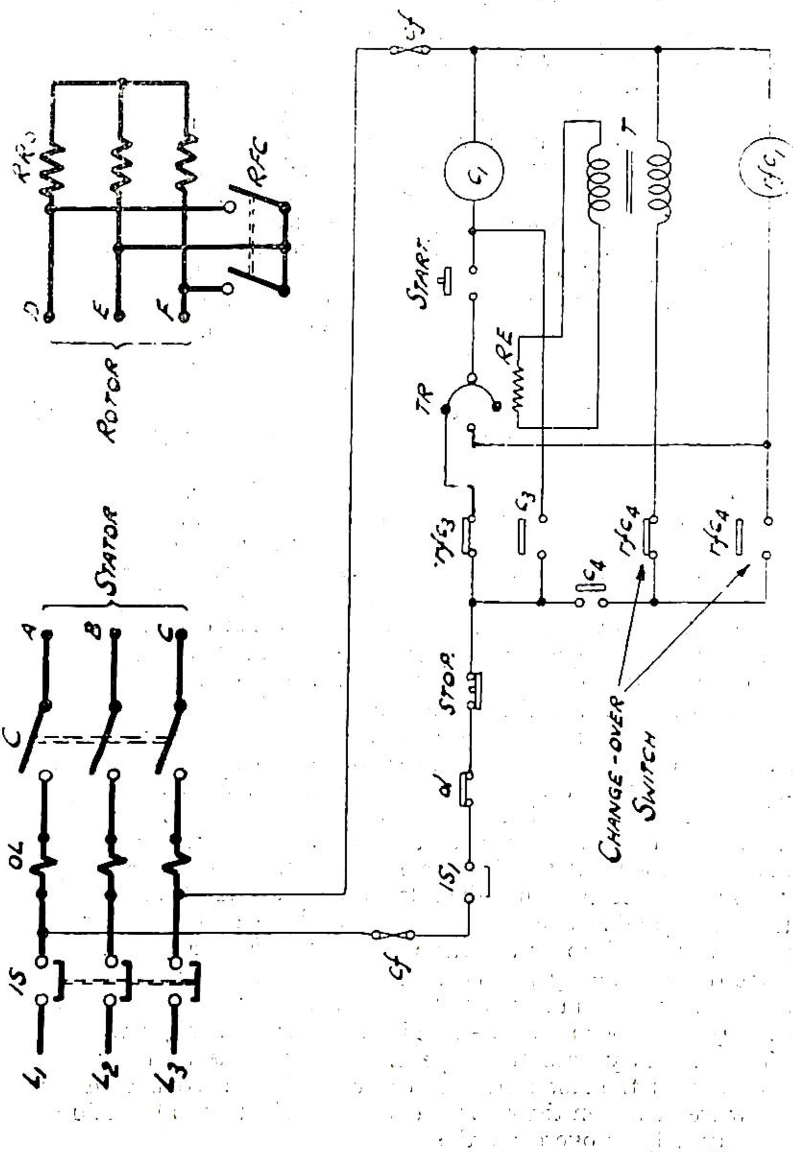
The simplest rotor starter is a combination of a straight-on starter for the stator and a choke-coil (two or three phase) for the rotor. The coil has an iron core and with decreasing rotor frequency the impedance will also decrease. At stand-still, with the rotor frequency equal to the stator frequency the impedance is high. At full speed the rotor frequency is nearly zero (2 to 3 cycles per second only) and the impedance of the choke-coil is practically identical with its ohmic resistance, which is kept at a very low value. Thus an automatic and gradual rotor control is obtained. Its chief disadvantage is the addition of impedance to the rotor circuit thus reducing the starting torque and decreasing the power factor. Furthermore, additional rotor resistance remains in circuit. To overcome the latter obstacle, an extra contactor can be provided, shorting the rotor choke at the end of the starting process.

Such smooth and gradual control is impossible with contactors to short circuit external rotor resistance. In automatic starters, usually only two to five steps are used to simplify the control. The number of contactors depends on the size of the motor. and with correct automatic timing startings is satisfactory. Only hand-operated starters where the cutting out of resistance steps depends on the skill of the operator, require a greater number of steps.

Current-controlled rotor starter schemes are usually simpler than the time-controlled schemes, since no relays, etc., are incorporated. They consist of a straight-on starter for the stator part, with extra normally closed switches in the starting circuit. Fig. 28 shows such a scheme. Switches 1 and $2rsc_3$ and rfc_3 are used to test the position of the rotor resistance contactors, so that the main contactor cannot close unless all the rotor contactors are open. After C has closed, c_2 will hold switch c_4 open until the starting peak has died down and then 1RSC closes. The coils c_2, $1rsc_2$ and $2rsc_2$ are not current coils, but shunt coils energised by the voltage drop across the respective resistance steps. This is done to avoid heavy series coils and reduce the size of the current relay. After the final rotor starting contactor RFC has closed, switch rfc_4 will open and de-energise the rotor starting contactors.

The difficulty with this type of starting is the uncertainty of the closing of the last resistance contactor in the sequence due to the low frequency in the rotor circuit. Rectifier operated hold-out coils may help to overcome this.

In order to introduce a definite time-delay feature into the scheme, the plunger of the current relay is only allowed to drop



ROTOR
STATOR
D
E
F
A
B
C
RFC
C
OL
IS
L1
L2
L3
START
TR
RE
T
C1
STOP
IS1
cf
C3
C4
CHANGE-OVER SWITCH

Fig. 29.

after a time interval, so that closing of the following contactor is controlled by either time-delay or current-delay, whichever predominates.

Pure time-control is possible by any of the time-delaying devices available, and to illustrate some of the possibilities, Figs. 29, 30 and 31 are shown.

Fig. 29 shows a small starter with only one rotor contactor, providing two starting steps. The timing is controlled by a thermal time-delay relay. It consists of a heating transformer T, a heating element RE and a bi-metal strip TR, acting as a change-over switch. The cold normally closed position is used for checking the initial position of the relay before closing C and rfc_3 serves the same purpose as regards the rotor contactor. The starting circuit is therefore completed via rfc_3 - TR - start-button - c_1. Contactor C is maintained by c_3 across TR and rfc_3. In closing, c_4 is made and energises T via rfc_4. RE is energised and heats up the bi-metal strip, which changes its position after a delay and closes the normally open contact, thus energising rfc_1. This causes RFC to close and rfc_4 to change over and maintain rfc_1 across TR. It also de-energises T to allow the time relay to reset and to prevent the bi-metal strip being heated continuously. Switch rfc_3 has to open after the normally open contact rfc_4 has closed, in order to maintain a supply to rfc_1 through TR until rfc_4 can take over this duty.

Fig. 30 shows a similar starting scheme, but with two rotor contactors and escapement-type time-delay relay. Again, switches rfc_3 and rsc_3 are included in the starting circuit to check the position of these contactors before C is allowed to close; c_3 maintains across them and c_4 energises the rotor control circuits. First $1tr_1$ is energised via rfc_4 and allows $1tr_2$ to close after a delay, energising rsc_1. In closing, RSC will energise $2tr_1$ via rsc_4 and finally $2tr_2$ will close after a delay and energise rfc_1. RFC closes and throws-over switch rfc_4, thus maintaining itself and cutting off the supply to the remaining rotor contactor and the timing relays. This switch rfc_4 should be of the make-before-break type to energise rfc_1 before the feed to $2tr_1$ is broken in order to prevent $2tr_2$ from dropping off before RFC has closed completely.

These two schemes provide purely time-delayed starting and no provision is made to allow the starting current any influence on the timing. Fig. 31 shows a scheme with a pilot-motor-operated master-controller, with an eddy current drag coil, energised in parallel with the last step of the starting resistance and braking a metallic disc fixed to the pilot-motor shaft. Current-time control can be obtained in this way.

To simplify the diagram, the main connections are shown as a single-line diagram only. Control by a remote float switch is assumed and rfc_3 and mc_1 are acting as start interlock switches.

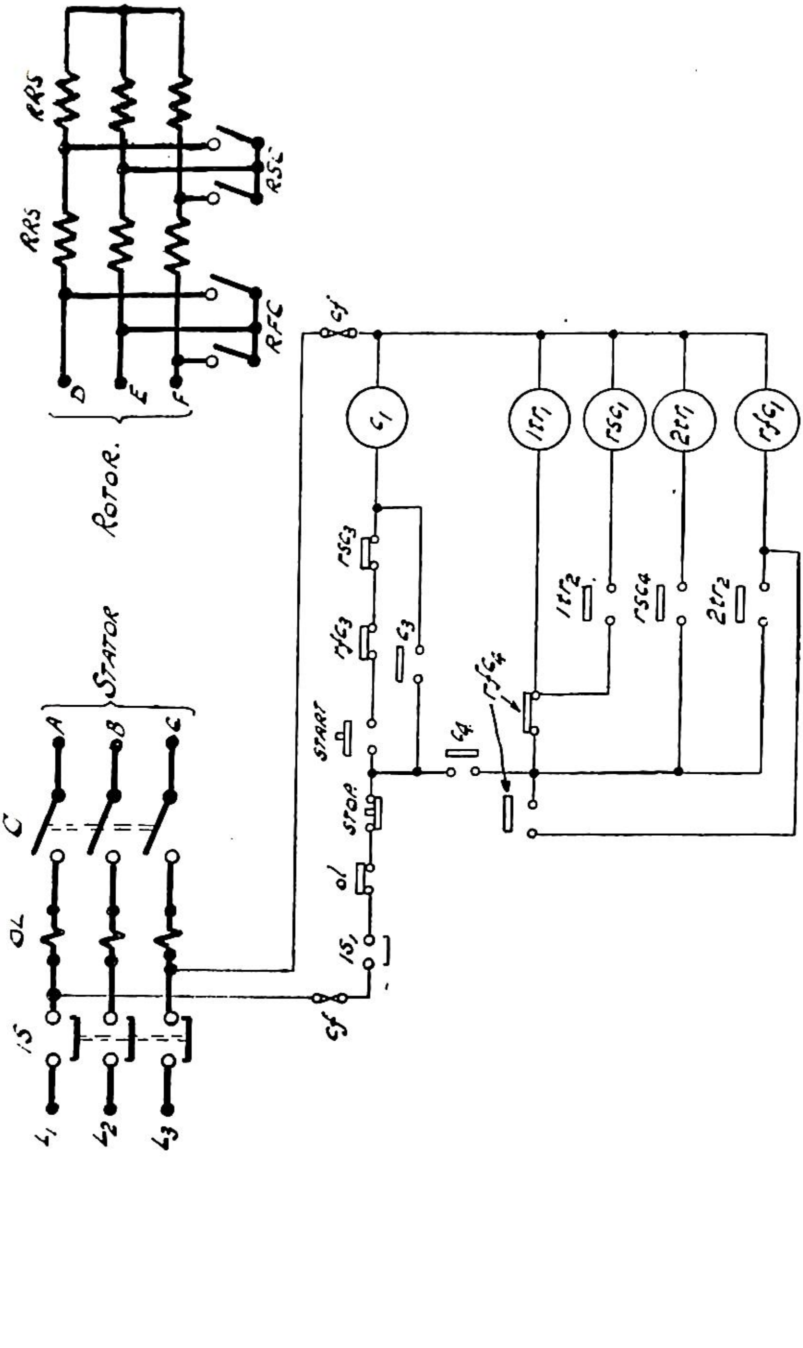

RRS
RRS
RSC
RFC
D
E
F
ROTOR.
STATOR
A
B
C
C
OL
IS
L1
L2
L3
cf
cf
START
STOP
ol
IS1
c1
1tr1
rsc1
2tr1
rfc1
rsc3
rfc3
c3
c4
rfc4
1tr2
rsc4
2tr2

Fig. 30.

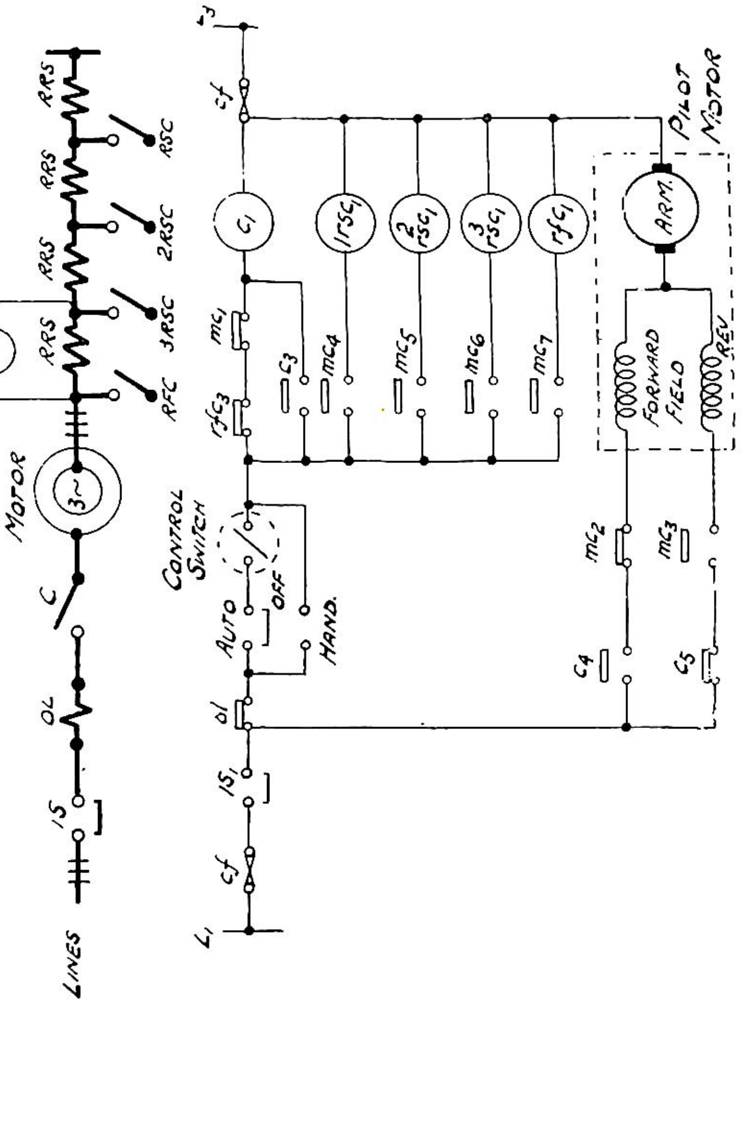

LINES
1S
OL
C
MOTOR
RRS
RRS
RRS
RRS
ED
RFC
3RSC
2RSC
RSC
L1
cf
1S1
ol
AUTO
OFF
HAND.
CONTROL SWITCH
rfc3
mc1
C3
mc4
mc5
mc6
mc7
C1
1rsc1
2 rsc1
3 rsc1
rfc1
cf
L3
ARM.
PILOT MOTOR
FORWARD FIELD
REV
mc2
mc3
C4
C5

Fig. 31.

The number of rotor contactors makes it difficult to provide an interlock switch for each, and therefore only the positions of the master-controller and the final starting contactor are checked. With C closing, c_4 also closes and energises the pilot-motor via the forward field winding of the latter. Switch mc_2 in this circuit acts as a limit switch to disconnect the pilot-motor, when the final running position is reached.

The master-controller switches mc_4 to mc_7 will close in the correct sequence and energise the respective rotor starting contactors 1RSC to RFC. These switches on the master-controller are arranged in such a way that after mc_7 has closed switches mc_4 mc_5 and mc_6 break again, tripping contactors 1RSC to 3RSC.

If the starter is tripped, switch c_5 closes and energises the pilot-motor through the reverse field and through switch mc_3. This latter switch is a limit switch which opens in the start position only. It will permit the pilot-motor to run in reverse and reset the master-controller. This resetting is effected at high speed, since the drag coil ED is not energised and no braking takes place. Contactor C can only be re-energised after the master-controller has reached the starting position, when mc_1 closes.

Other types of controllers can be used instead of the pilot-motor-driven master-controller. For instance, a solenoid with a delayed plunger which, when lifted, will close switches on different levels. These switches in turn energise the rotor resistance contactors. A similar scheme for the control of D.C. starters is described later and shown in Fig. 38.

Instead of using controllers to operate switches energising the rotor contactors, main current switches can be operated directly. This method is adopted if the number of contactors becomes too great or the contactors too heavy on account of the high rotor currents. In this case a bigger pilot-motor has to be used and eddy current braking is ruled out because it would not be sufficiently effective to influence the starting time. A current relay is employed instead, interrupting the circuit to the pilot-motor and permitting it to continue to run only after the current peaks have dropped to a present value.

If inching is required, the usual relay is incorporated, but the rotor contactor control circuit is only energised when the "start" button is depressed. When inching, the stator contactor only closes and the motor runs with all resistance in circuit.

Variable speed rotor starters do not usually make use of contactors, since their number would become too big and the control circuits rather complicated. Instead, either pilot-motor-driven regulators are used, or liquid rheostats, where a pilot-motor raises or lowers the electrodes. The latter kind, however, is only employed for very large motors.

A combination of regulator and contactor starter is possible, in so far that contactors are used to shorten the steps required for starting and the regulator takes care of the remaining rotor resistance. It is possible also to use part of the regulator for starting and the rest of the range for regulating purposes.

Due to the heavy current, the contacts of the regulator are big and the brush must be stopped only when completely covering one contact. This is done by means of limit switches, which allow only step-by-step movement of the brush. Relays for the forward and reverse motion of the pilot-motor are also required.

Fig. 32 shows a scheme for a regulator starter without special starting steps. The starting of the motor is practically straight-on since the resistance is only big enough to produce a speed reduction of not more than 20%. Main contactor coil c_1 is energised via a start interlock switch RR_1 closed by the regulator in the start position only. Switch c_3 maintains c_1; c_4 closes and prepares the circuit for the accelerating relay coil ar_1 and c_5 opens to make the retard button operative.

The motor is now running at slow speed with all rotor resistance in. To raise the speed the accelerate button has to be depressed, thus energising ar_5 through c_4, RR_4 and rr_4. Switch RR_4 is the maximum speed limit switch and rr_4 the electrical interlock with RR. The relay closes and energises the pilot-motor in the forward direction via ar_5, and switch ar_3 maintains the relay through switch RR_3. This switch RR_3 is the "step-by-step" switch of the regulator, breaking each time the brush covers a contact. It is operated by a cam on the regulator spindle. In this way the regulator is only allowed to move from one contac to the next unless the accelerate button is kept depressed. When the brush fully covers a contact, RR_3 opens and de-energies ar_1, which drops out.

On depressing the retard button, a similar circuit for the retard relay RR is closed. Maximum limit switch RR_4 is replaced by minimum speed-limit switch RR_5 and switch cc_5 in parallel to the retard button ensures the resetting of the regulator when the stator is tripped. No new start is possible until RR_1 has reclosed.

(4) Braking.

Two schemes for braking A.C. induction or synchronous motors are used, viz., reverse current (or "plug") braking and D.C. injection braking. The former method is generally only used for smaller squirrel cage motors (especially in machine tool drives) in combination with straight-on starting, whereas D.C. braking is used for all kinds of motors and starters.

A disadvantage of reverse current braking is the possibility of reversal of rotation. To prevent this, either time delay relays

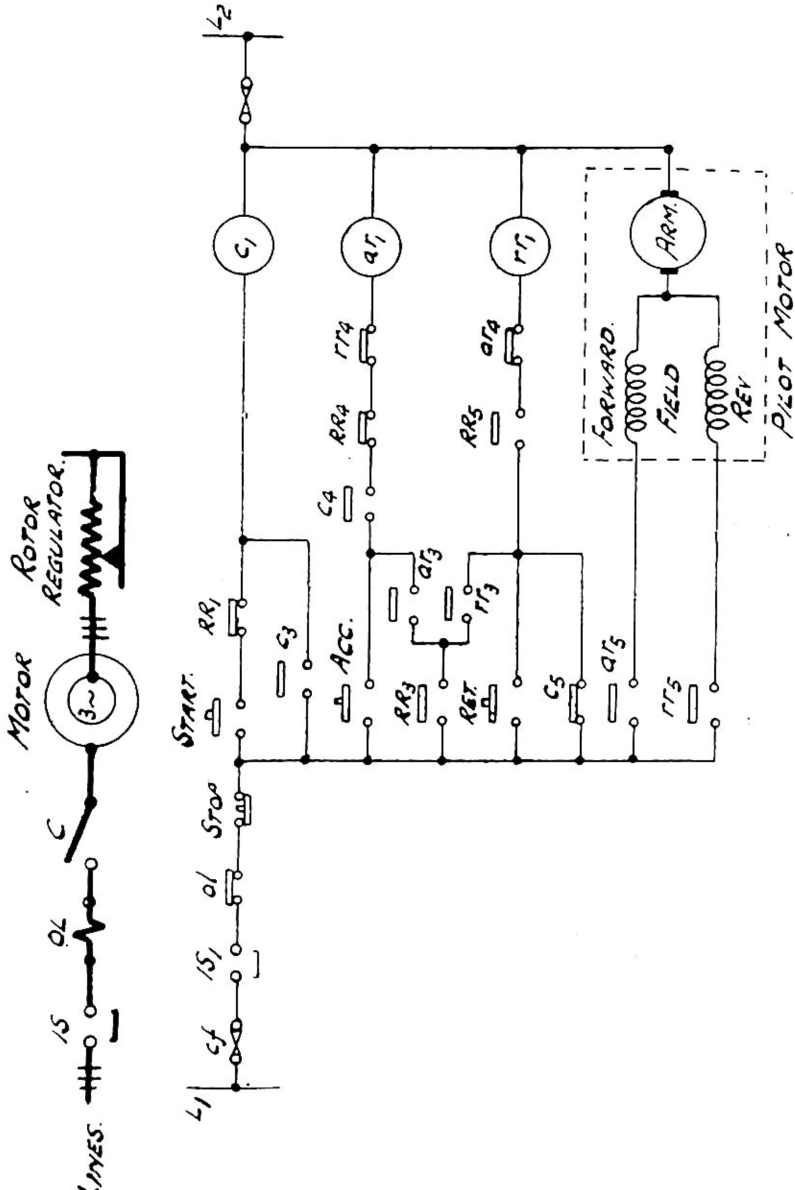

LINES
1S
OL
C
MOTOR
3~
ROTOR
REGULATOR.
L1
cf
1S1
ol
STOP
START.
RR1
C3
ACC.
RR3
RET.
C5
ar5
rr5
ar3
rr3
C4
RR4
rr4
RR5
ar4
C1
ar1
rr1
ARM.
FORWARD.
FIELD
REV
PILOT MOTOR
L2

Fig. 32.

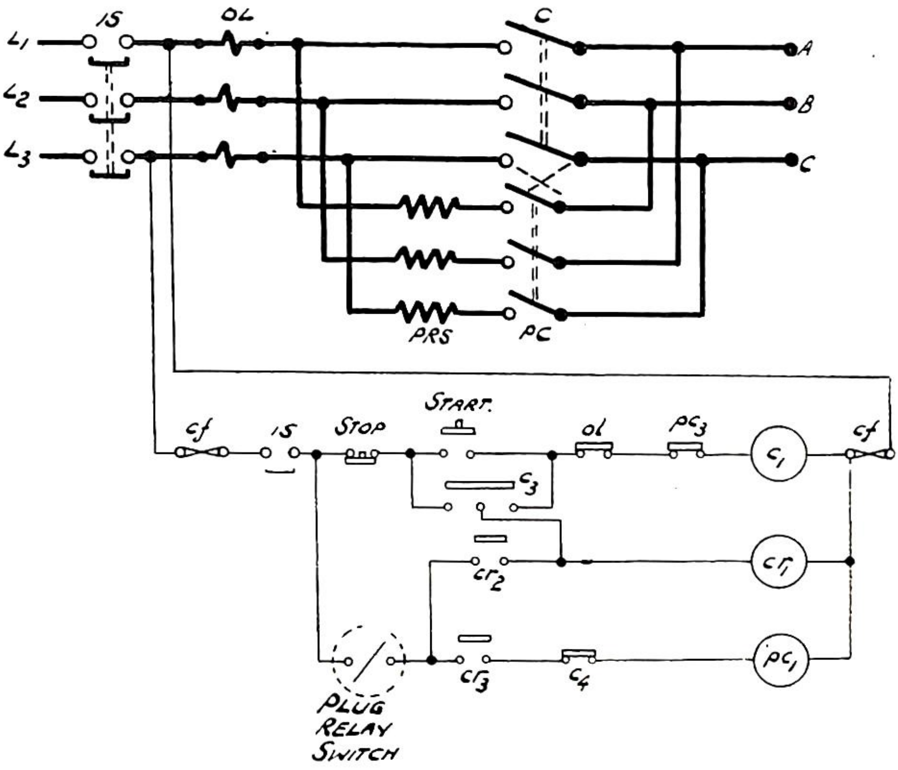


Fig. 33.

have to be employed to interrupt the supply to the stator or centrifugal switches must be incorporated, operated from the motor shaft. As soon as the motor speed drops to a low value (near standstill) the control circuit to the brake contactor is interrupted. If the operator can watch the motor, these extra controls may be omitted, braking taking place only for the length of time the brake button is depressed.

Time delay relays must be adjusted on site, the delay varying according to motor speed and inertia of the drive.

Fig. 33 describes a scheme for a straight-on starter with plug-braking and control switch on the motor shaft. A series resistance is incorporated in the braking circuit to reduce the current.

On starting, c_3 maintains c_1 and also energises control relay coil cr_1, which is maintained through cr_2 and the plugging switch; switch cr_3 closes and prepares the circuit for the plug contactor coil pc_1 through c_4, which is open as long as C remains closed. When

the stop button is depressed, c_1 is tripped and c_4 completes the circuit to pc_1, which closes and brakes the motor to standstill, when the plugging switch will open. Switch pc_3 prevents restarting until PC is tripped.

D.C. injection-braking does not suffer from the same disadvantage, but where D.C. is not available, special provisions have to be made to secure a supply. A D.C. voltage of such a magnitude is applied that approximately the full-load current is passed through the windings. Metal rectifiers are generally used for supplying this voltage. They are energised from transformers and the braking time is controlled either by centrifugal switches on the motor shaft, or by timing devices. Since the braking effect is a fairly severe one, only short time delays are required.

In the case of star-delta starters it is usual to connect the stator in delta in order to allow all three phase windings to partake in the braking process. In the case of rotor starting, either the total or part of the starting resistance has to be reinserted for reasons described in Chapter I.

Fig. 34 shows a straight-on starter for an induction motor with squirrel cage rotor adapted for D.C. injection braking. To control the braking process, time-delay relay TR is incorporated, which allows switch tr_2 to remain closed for a while after coil tr_1 is de-energised. The D.C. supply is obtained from a metal rectifier RF energised from auto-transformer AT. As soon as brake contactor BC closes, the auto-transformer is connected to the lines and D.C. is supplied to the motor terminals A and B. A thermal overload relay RT is incorporated in the A.C. circuit of the rectifier to protect the latter against excess currents. The trip switch *rt* is in series with *ol*, de-energising the control circuit if tripped.

The control scheme for contactor C is the same as for a straight-on starter, with the exception of switch bc_3 on the brake contactor, which serves as an interlock. With C closing, tr_1 is energised and closes switch tr_2, preparing the circuit for bc_1. Since switch c_3 is open, BC remains open. When C is tripped by depression of the stop button, the circuit to bc_1 is completed and BC closes and D.C. is supplied to the motor until tr_2 trips on account of tr_1 being de-energised.

CHAPTER V.—AUTOMATIC D.C. STARTERS.

(1) General Remarks.

As already explained in the first chapter, it is important to provide a strong motor field during starting, and in the case of variable speed starters, special precautions have to be taken. Two methods are employed; either an interlock switch is fitted to the shunt field regulator, closed only in the "all resistance out" (*i.e.*, full-field) position or a special field or accelerating relay is in-

corporated. In the first case, the speed has to be readjusted after each starting process, since it is necessary to return to the regulator in the full-field position before starting is made possible.

In the second case the regulator may remain in any desired position and the relay automatically short circuits all or part of the field resistance during starting and after the motor has gained sufficient speed, accelerates it further until the pre-set speed is reached. For this purpose the relay is generally provided with two coils, which are either two series coils or one is a series and the

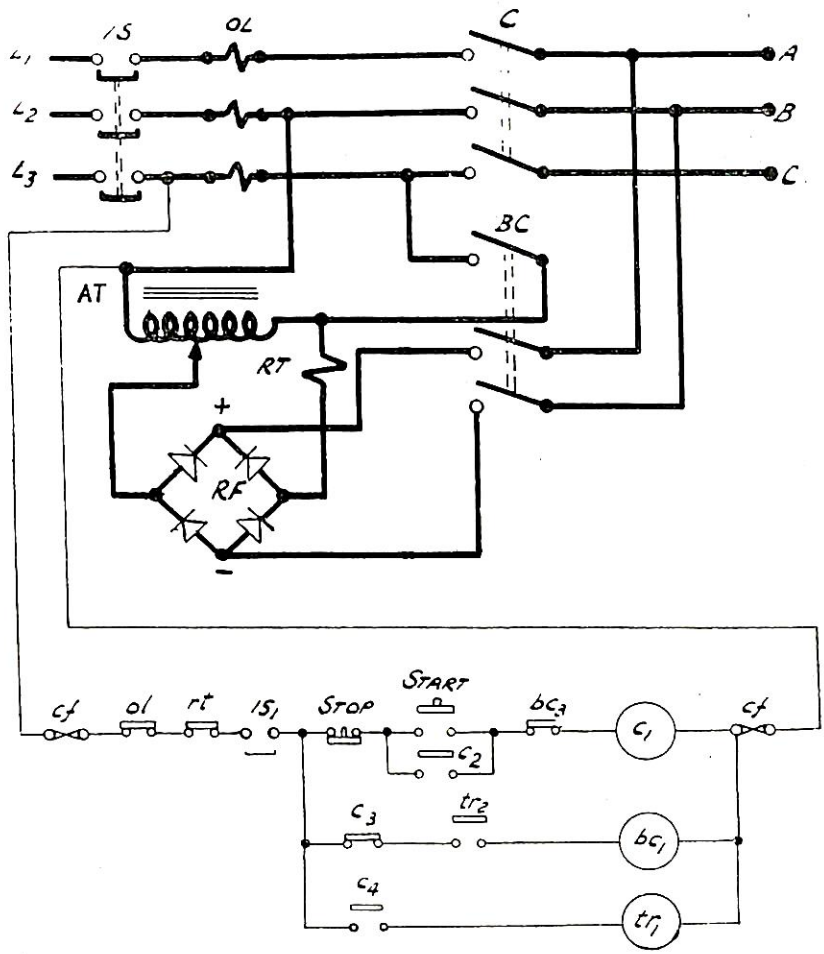


Fig. 34.

other a shunt coil. The second series coil or the shunt coil is required to ensure closing of the relay during starting and is either shorted or disconnected after all starting-resistance has been cut out. The series coil left in circuit is only strong enough to keep the relay closed under peak conditions of the armature current. The relay contacts are connected in parallel with the field rheostat (see Figs. 38 and 42) and thus short-out this resistance when they are closed. After completion of the starting process, the series coil left in circuit will allow the relay to drop out, provided the current has dropped sufficiently and field resistance is inserted. Should this weaken the field too much with the motor speed still low, the armature current will rise again and the relay will reclose. The motor, however, will have accelerated a little. Re-closing of the relay again provides a strong field and the armature current drops again. This will cause the relay to fall out again and this process is continued until the motor has reached its full speed. Thus the relay will close and open rapidly ("flutter") and this action accelerates the motor by short-circuiting and then re-inserting part or all of the field resistance. Severe sudden overloads may also cause the relay to close and thus increase the torque and reduce the current peak.

It is important that little arcing should occur on the relay contacts. Carbon contacts are sometimes used to assist this and other arc suppressing means are also adopted, *e.g.*, blow-outs may be fitted and generally a condensor is also connected across the relay contacts.

A number of special relays are required in connection with D.C. schemes, for example, the excess voltage relay, connected across the motor armature to prevent excessive speeds of the motor on hoists or lifts when lowering with regenerative braking. Should the supply voltage fail, no braking would take place and the solenoid brake, the shunt field and the control circuits if connected across the armature would be energised from the latter and would cause the main contactors to hold in. The speed, and with it the generated E.M.F., will increase and cause the excess voltage relay to trip the control cuircit. The main contactors open, the solenoid brake is disconnected and will operate and brake the hoist.

(2) Back-(Counter) E.M.F. Starters.

This method of starting a D.C. motor is a very simple one and makes use of the E.M.F. generated in the armature which is proportional to the speed of the motor. The operating coils of the resistance short-circuiting contactors are connected across the motor armature and are arranged to close the contactors when the back E.M.F. has reached certain values, *i.e.*, when the motor has accelerated up to certain speeds. Thus step-by-step starting can be obtained. However, if more than one or two contactors are

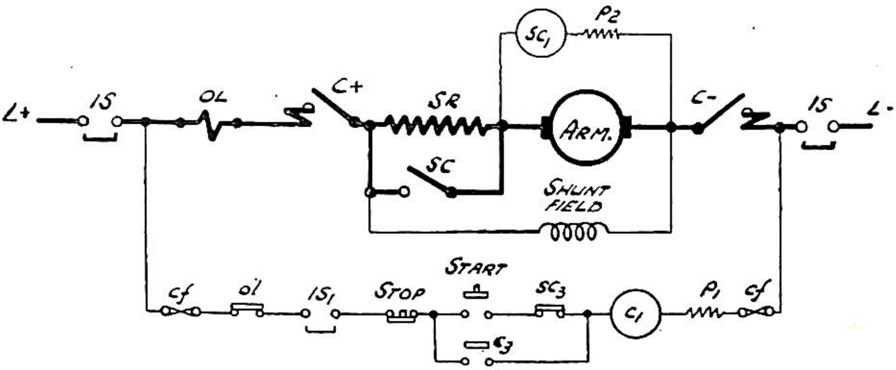


Fig. 35.

used, the difference in E.M.F. values at which these contactors should close is comparatively small. It is difficult to adjust contactors to close satisfactorily in the correct sequence, chiefly due to the fact that the coil resistance varies with the temperature. To overcome this effect partially high series "swamping" resistances with negligible temperature coefficients are employed.

This type of starter is much in use where one or two starting contactors only are required, *i.e.*, with small and medium-sized motors and light starting torques. Heavy starting loads might prevent the motor from accelerating sufficiently to allow the contactor to close, and burning out of the starting resistance would result.

Undue drops in the main voltage may also prevent the motor from correct acceleration.

Fig. 35 shows a scheme for such a two-step back E.M.F. starter for constant speed. The control circuit is the same as for a straight-on starter, except that switch sc_3 is incorporated in the starting circuit to act as interlock and to prevent C from closing should SC be closed (due to "sticking"). The shunt field is energised immediately C closes and SC will close after a certain back E.M.F. has been built-up. Permanent resistance p_1 is incorporated to allow one standard coil to be used for a range of voltages.

In Fig. 36, a similar scheme for a constant speed reversing starter is shown. A compound wound motor is assumed, and it should be noted that only the connections to the armature are reversed, but not those to the series field. The reversing is done by means of the mechanically and electrically interlocked contactors FC and RC. Both have auxiliary contacts, fc_5 and rc_5, which are connected in parallel to energise the shunt field. A discharge resistance DR is connected in parallel to the latter to

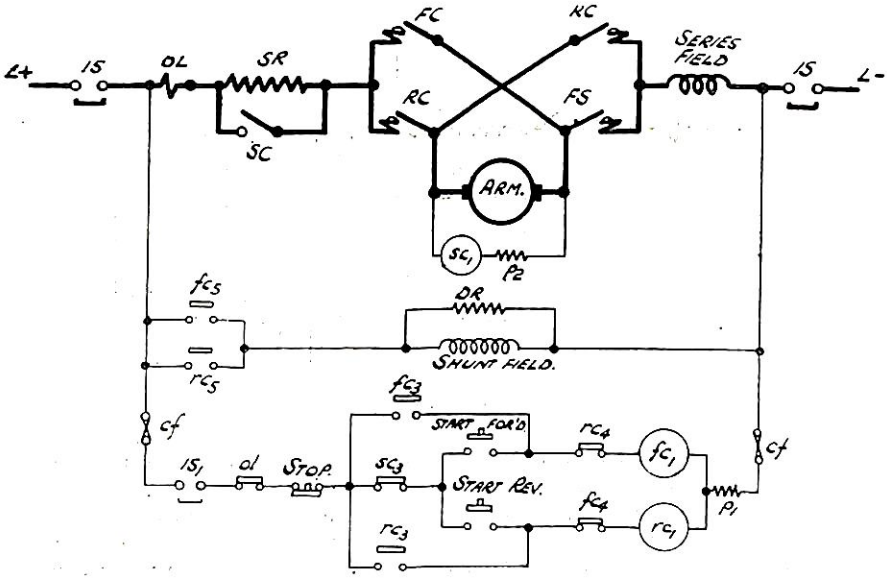


Fig. 36.

provide a path for any surges when opening the field circuit. Switch sc_3 acts as start interlock in both starting circuits (forward and reverse) and fc_3 or rc_3 maintain across it and the respective push button.

The stop button has to be depressed for reversing and the reverse contactor can only close after the motor has nearly stopped (preventing energising the still rotating armature), since contactor SC will only fall out after the generated E.M.F. has been reduced sufficiently. Contact sc_3 prevents restarting with SC still closed.

(3) Time-Delayed Starters.

Time delay relays or other delaying devices can be employed for the control of the starting contactors in place of current or back E.M.F. control. Relays are only used where one or two starting contactors are to be controlled ; if a great number of steps is required other means are adopted.

Fig. 37 shows a scheme for a starter with one starting contactor and for constant speed duty. Switches sc_3 and tr_2 are start-interlock switches to test the position of these components before C is allowed to close. Auxiliary switch c_3 is used for a number of purposes ; it maintains c_1, inserts the resistance er_2, which acts as economy resistance, and also energises time relay coil tr_1 via switch tr_3,

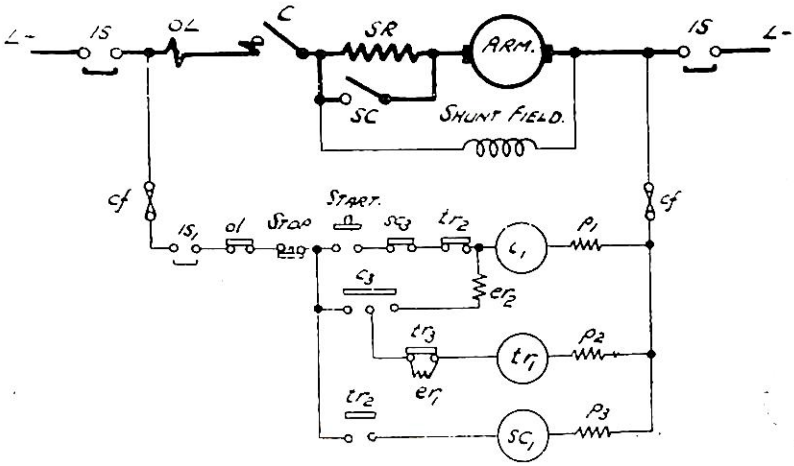


Fig. 37.

which acts as economy switch for TR, inserting resistance er_1 in the coil circuit. The relay switch tr_2 will close after a delay and energise starting contactor SC.

(4) Automatic Multi-Step Starters.

A number of multi-step starters are available : contactor-type starters with accelerating contactors, motor-operated regulator starters, solenoid-operated starters.

The contactor-type starters, like the A.C. rotor starters, employ either current or time or current-time control. In the first case current relays (see Fig. 14) or current lock-out contactors (see Fig. 42) may be used.

Time control can be effected by a series of time relays or by master-controllers (motor-driven or solenoid-operated). The control scheme for a starter with pilot-motor-driven master-controller is identical with the one shown in Fig. 31 for a rotor starter and the eddy current drag coil will again be energised by the voltage drop across the last starting resistance step.

Fig. 38 shows a scheme for a variable speed, solenoid-controlled starter. The master-controller consists of a lifting solenoid the plunger of which carries a contact bar which engages with a number of fixed contacts set at varying distances from this bar. As the plunger rises, this bar will short-circuit successive resistance steps.

The movement of this plunger may be delayed by any of the devices described in Chapter II., par. 5. Where a gear drive is used, this can be provided with eddy current braking, permitting additional current control. The brake coil can be either a series

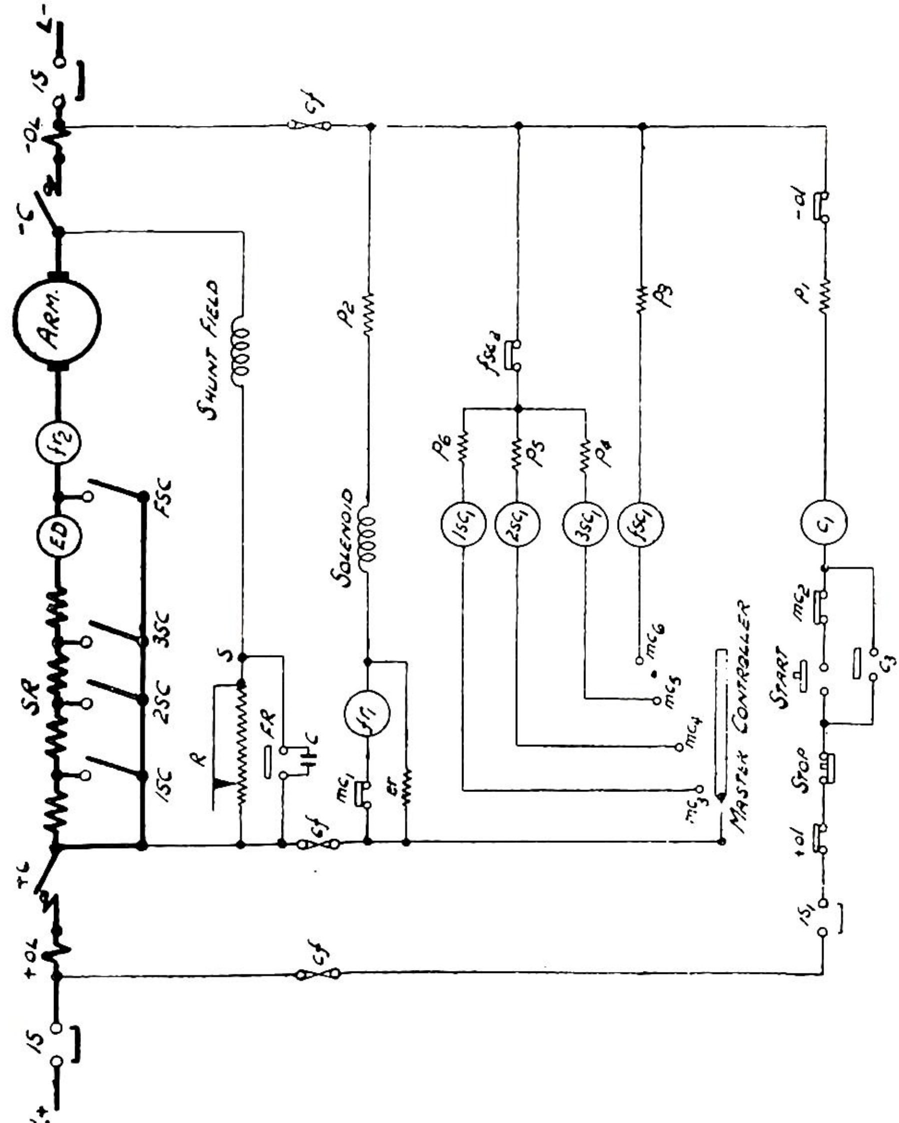

ARM.
SHUNT FIELD
SOLENOID
MASTER CONTROLLER
START
STOP
SR
FSC
3SC
2SC
1SC
ED
FR
P2
P3
P1

Fig. 38.

coil energised by the starting current and short-circuited after the starting process is completed, or a shunt coil energised by the voltage drop across the last resistance step. In Fig. 38 a series coil is shown, shorted by the final starting contactor FSC. The starting contactors SC are never called upon to break circuit, but only make circuit; it is therefore not necessary to provide them with blow-out coils.

Because the starter is of the variable speed type, a field relay is incorporated, having a series coil fr_2 and a shunt coil fr_1. The latter is energised through switch mc_1 on the solenoid controller and when the controller has reached its final position, this switch will open and disconnect fr_1. In order not to increase the coil current of the solenoid unduly a resistance *cr* is inserted, acting as a compensating resistance for fr_1.

To start the motor, contactor coil c_1 is energised through the start button and a switch mc_2, which acts as an interlock to ensure that the solenoid plunger is in the bottom position before C is allowed to close. Switch c_3 maintains the coil circuit for C. The closing of contactor C also energises the shunt field, the solenoid of the controller and fr_1. The plunger of the solenoid will commence to rise and close switches mc_3, to mc_6 in the correct sequence, thus energising the starting contactors 1SC, 2SC, 3SC, and finally FSC. Switch fsc_3 on the final starting contactor will interrupt the coil supply to the starting contactors SC and cause these to drop out; their coils therefore need only be short-time rated.

No discharge resistance for the shunt field is required, since a completely closed discharge path is provided through the shunt regulator R, the starting resistance SR and the armature.

If the starting current is not too heavy (below 100 to 150 amps) the solenoid may be able to control the main circuit directly and the starter can thus be considerably simplified by the omission of the starting contactors. The same current-time control features as described above for the solenoid-operated controller, can be maintained. A scheme of this kind is shown in connection with Figs. 41 and 45, and a typical example of such a starter is illustrated in Fig. 39.

Pilot-motor-driven D.C. starter-regulators are mainly used for automatic speed control. The starter and regulator are combined in one unit. No interlocks for starting with full field are required, since the brush always starts from the zero position with the field resistance short-circuited. It is possible to incorporate pre-set speed features on the regulator and to accelerate the motor up to this speed after starting is completed. Any further increase in speed can then be controlled by the "Accelerate" push button. A pilot-motor driven starter-regulator, however, without pre-set speed features, is shown in Fig. 40.

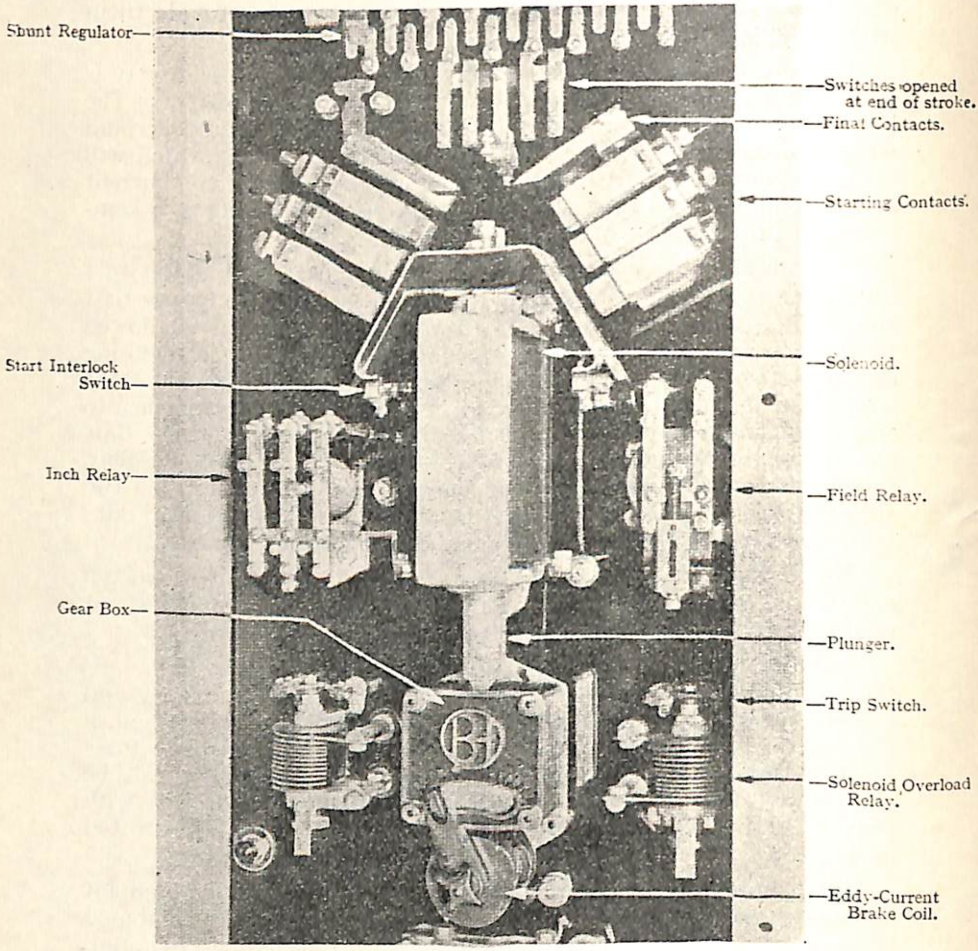


Fig. 39—D.C. Variable Speed, Solenoid-type Auto-Starter, with Field Relay, Inch Relay, Solenoid Overload Relays without Dash-Pots and Eddy-Current Retarding Device.

The regulator requires a number of limit switches for its correct operation and the position of these is shown above the regulator in the diagram. Switch LS_1 serves as start interlock and is closed in the start position only. It makes it impossible for C to close, unless the regulator is in this position. Switch LS_2 is the limit switch stopping the pilot motor after the starting resistance has been short-circuited and allowing further acceleration by the aid of the push button. It also enables the pilot-motor to run up the regulator to this position by energising the forward field through switch c_4 on the main contactor, closed, when the latter has closed. Switch LS_3 is the maximum-speed limit switch and switch LS_4 the minimum-speed limit switch, stopping the pilot-motor when resetting the starter.

As soon as the main contactor is closed, the pilot-motor starts up and accelerates the motor by shorting the starting resistance. It continues to run until LS_2 opens. This switch is of the double-pole type, with the second pole in the reverse field circuit of the pilot motor to prevent this field being energised by depressing the "Retard" button whilst the pilot-motor is still running in the forward direction during starting. The "Retard" button is only operative after LS_2 has tripped. Should, during the retarding process, the position of the regulator be reached, in which LS_2 starts to move again, the pilot-motor circuit would be interrupted by LS_2 and any further retarding prevented.

This scheme provides time control only for starting.

Inch and "crawl" features can be added by the addition of control relays and additional limit switches on the regulator. Inching can only be done with all starting resistance in circuit. "Crawling" is a term applied to very slow but continuous running required for setting-up or adjusting the machine.

(5) Dynamic Braking.

Next to reverse current braking, which is used only for small and specially-built motors, dynamic braking is the most effective and retards the motor nearly to stand-still. It is generally used for series and shunt-wound motors.

Either standard line and accelerating contactors with a separate brake contactor for short-circuiting the armature through a resistance can be employed or double throw dynamic brake contactors are used which complete the braking circuit in the de-energised position when the contactor armature has dropped off.

The braking resistance can be either a separate resistance or it may be possible to use the starting resistance for this purpose. To provide a constant braking torque it is necessary to grade the braking resistance in steps similar to the starting resistance.

It is important that the motor field is maintained during the braking process. A separate field contactor is required if the field

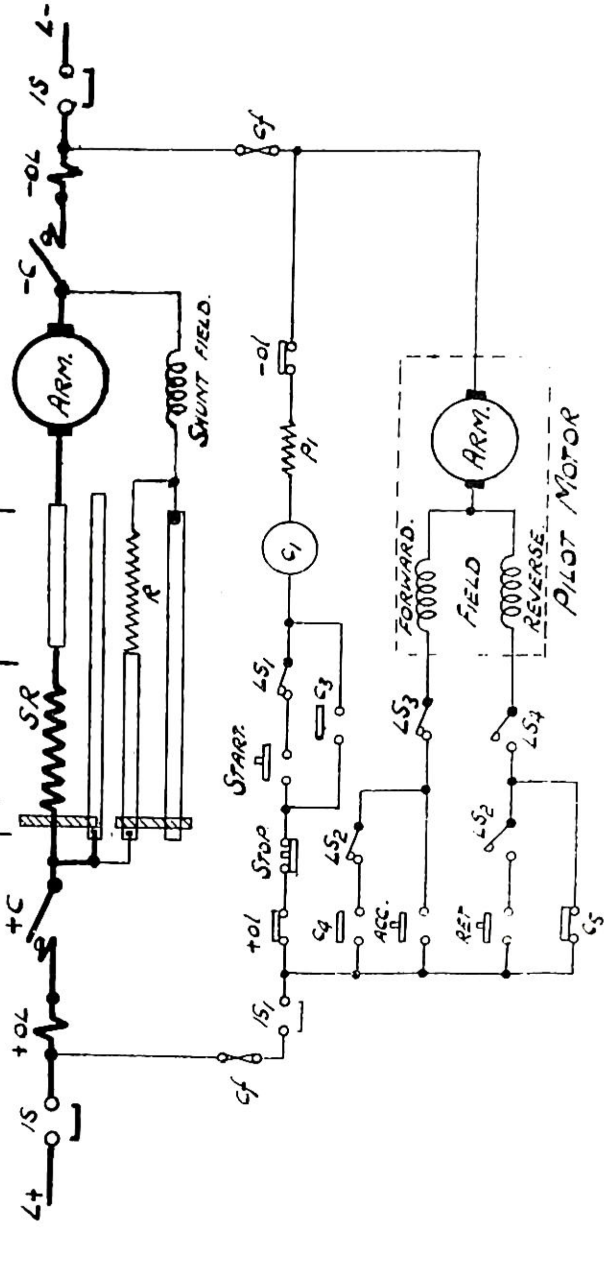

L+
1S
+OL
+C
LS1 LS4
SR
LS2
LS3
ARM.
-C
-OL
1S
L-
R
SHUNT FIELD
Cf
1S1
+ol
STOP
START
LS1
C3
C1
P1
-ol
Cf
C4
LS2
ACC.
LS3
RET.
LS2
LS4
C5
FORWARD
FIELD
REVERSE
ARM.
PILOT MOTOR

Fig. 40.

is energised from the mains. Alternatively the field can be connected across the armature and is then energised from the generated E.M.F.

The control of the braking process is effected by a relay, which is connected in parallel to the motor armature and energised by the E.M.F. generated during braking. This relay will drop out after this E.M.F. has decreased to a sufficiently low value, at which no more effective braking takes place. A relatively big series resistance will have to be incorporated in its coil circuit for temperature compensation.

Fig. 41 shows a scheme of an automatic solenoid-operated starter with dynamic brake contactor DBC and part of the starting resistance used as brake resistance. It is assumed that the main contactors C are of a larger size, hence each contactor will be of the single-pole type. The two operating coils c_1 are connected in series. Contactor DBC and the two main contactors are electrically interlocked by switches dbc_3 and c_4. Switch as_3 in the starting circuit acts as a start interlock for the auto starter and is closed only when the plunger is in the bottom position. On closing C, c_5 closes and energises mfc_1, which in turn will close and energise the field. A discharge resistance is connected in parallel to the latter. After C has closed, the auto-starter solenoid is energised through as_4, which acts as an economy switch and inserts er_1 after the plunger has reached the top position.

The starter is of the constant-speed type and the motor compound-wound. The series field is not incorporated in the braking circuit for reasons described in Chapter I.

When sufficient back E.M.F. is generated in the armature, the relay BCR will close, but this has at the moment no further effect. Depressing the stop-button trips contactors C. BCR remains closed due to the armature E.M.F. Thus the supply to the field contactor coil mfc_1 is not interrupted and MFC remains closed. Switch bcr_2 is closed and switch c_4 recloses when C opens providing a circuit to dbc_1 and DBC closes, inserting the braking resistance in the armature circuit. After the E.M.F. of the motor has decreased sufficiently BCR will open and de-energise MFC and DBC and only now is the starter ready for a restart. It is important that switch c_4 breaks before c_5 makes, to prevent DBC from closing when C is closing.

A scheme for a variable-speed reversing starter with one lock-out starting contactor and with double-throw brake contactors is illustrated in Fig. 42. The start contactor is provided with a series hold-off coil and a shunt-closing coil. Field relay FR has two series coils fr_1 and fr_2 and fr_1 is shorted after SC closes, leaving fr_2 in circuit for the acceleration of the motor.

Switch sc_3 in the coil circuit of the main contactors serves a double purpose—it is interlock and economy switch. Should SC

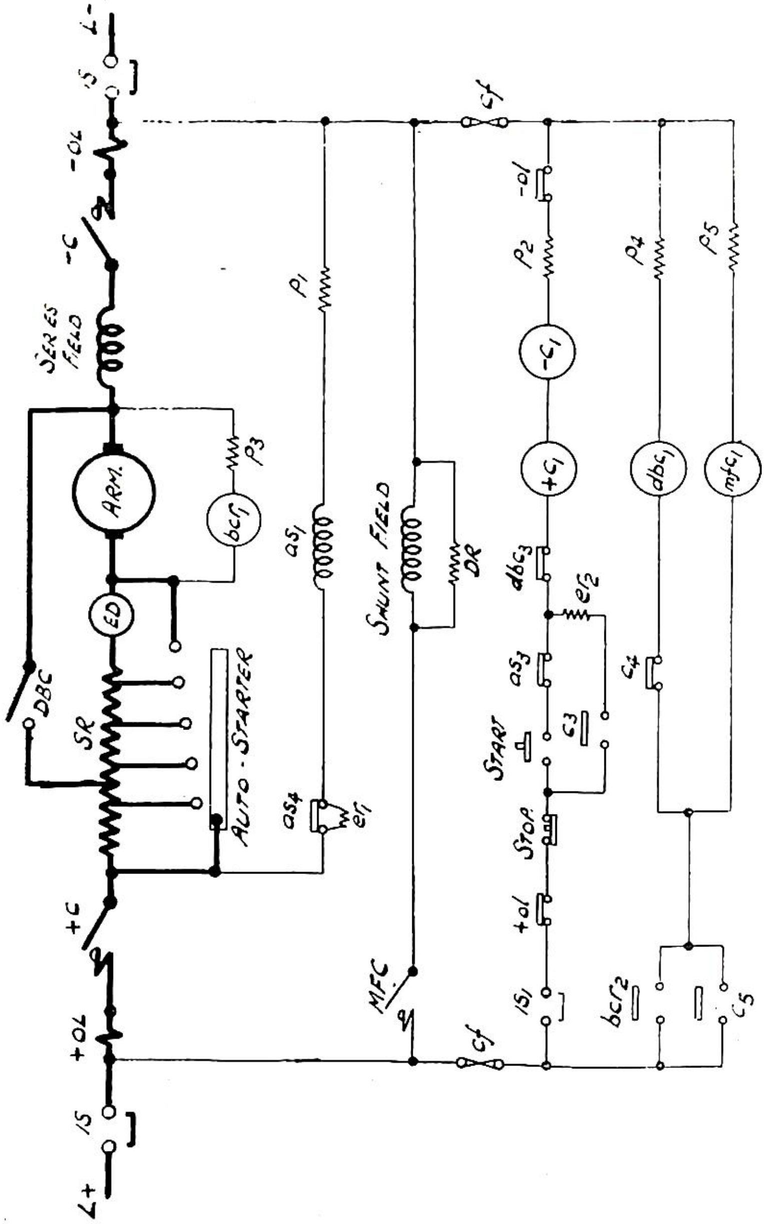

L-
S
-OL
-C
SERIES FIELD
ARM.
P3
bcr1
ED
DBC
SR
AUTO - STARTER
+C
+OL
1S
L+
P1
as1
as4
er1
SHUNT FIELD
DR
MFC
cf
cf
-ol
P2
-C1
+C1
dbc3
er2
as3
C3
START
STOP
+ol
1S1
P4
dbc1
C4
bcr2
P5
mfc1
C5

Fig. 41.

be closed, sc_3 is open and *cr* in circuit. The voltage across the coils fc_1 or rc_1 is then not sufficient to allow the closing of these contactors. If sc_3 opens after FC or RC have closed, it inserts *cr*, which then acts as an economy resistance only. The contactors FC and RC are mechanically and electrically interlocked. Either of them closing will energise shunt ccil sc_1 via fc_5 or rc_5.

If the starter is tripped, contactor FC or RC drops out and will complete the brake circuit for the motor through fc_2, dynamic brake resistance DBR, -rc_2, - RC, - armature and FC. Schemes of this kind are very often employed for machine tools where quick stopping is essential.

CHAPTER VI.

MOTOR-GENERATOR CONTROL SCHEMES.

Two important types of motor-generator schemes are in general use, Ward-Leonard and booster control. A variation of the first, the Ward-Leonard-Ilgner scheme, whereby a fly-wheel is added to the motor-generator set, is used chiefly for the drive of heavy and varying loads, *e.g.*, rolling mills, etc., where heavy load peaks occur. The energy stored in the flywheel will provide the additional energy to satisfy the peak demand and thus the load on the mains is reasonably free from load peaks. If A.C. is available wound rotor motors are used for driving the generator, and special regulators are required to assist the fly-wheel in storing or supplying energy. These regulators are mainly liquid rheostats, the electrodes of which are controlled by a "torque motor." This is a squirrel cage motor energised by the slip energy of the A.C. driving motor. With increased load, the slip increases and thus also the torque of the pony motor which lifts the electrodes against the action of springs or weights and so inserts rotor resistance, decreasing the motor speed and inducing the fly-wheel to give off energy. Instead of the liquid rheostat a controller may be employed, energising or de-energising resistance contactors and controlling the rotor resistance in this way. Where D.C. mains are available, the main driving motor is compound wound ; load peaks will cause the speed of the motor to decrease considerably and the flywheel will return some of its stored energy.

(1) Ward-Leonard Control.

This method of control is generally employed where smooth speed control is required either with or without reversing motion of the motor. It may be combined with regenerative braking or dynamic braking, and is used chiefly where A.C. only is available, since with

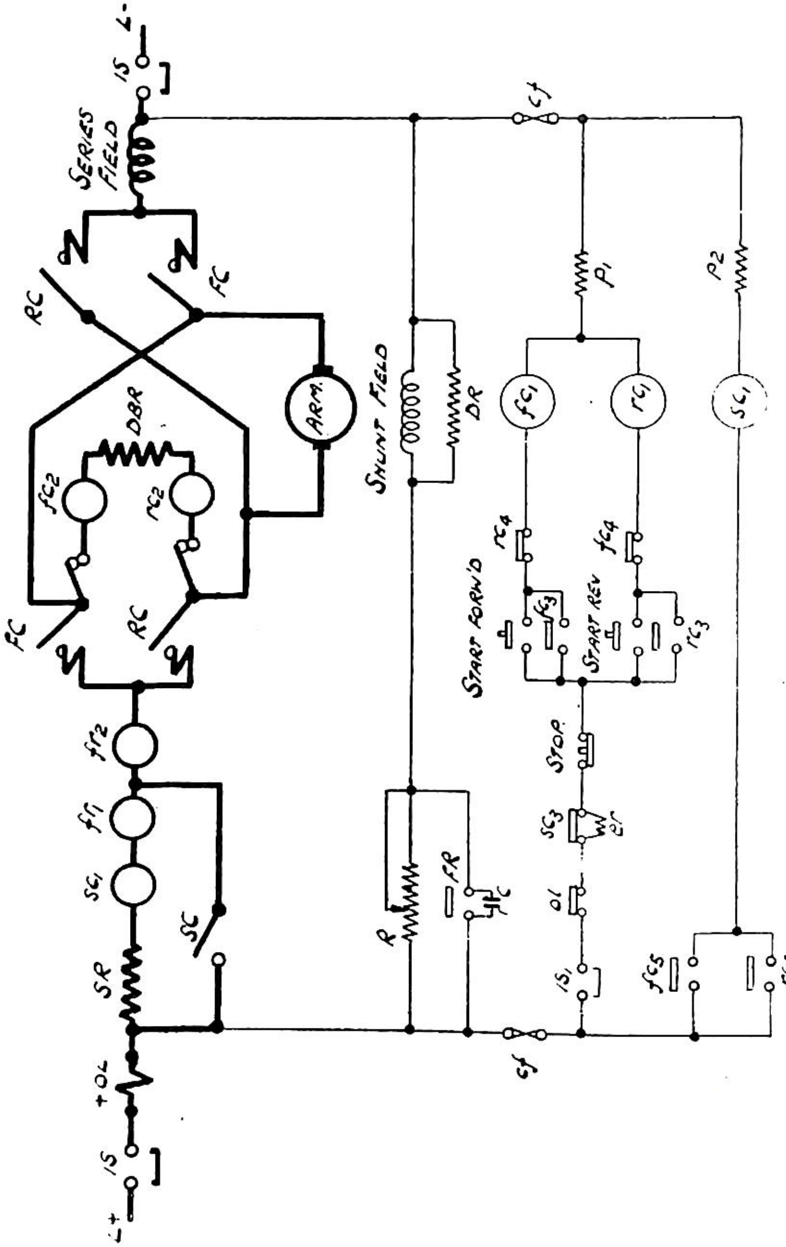

SERIES FIELD
SHUNT FIELD
ARM.
DBR
DR
START FORW'D
START REV
STOP
P1
P2
L+
L-

Fig. 42.

D.C. mains a booster set might be more economical on account of its size.

A separate exciter is required driven by the M.G. set motor for providing the excitation current for generator and motor fields, thus bringing the total number of machines required to four. Alternatively, rectifiers can be used for this purpose if A.C. is available.

The generator field regulator is usually of the potentiometer type, in order to provide the generally large range of generator field current and also because it is simple to obtain field reversal.

A scheme, with double-throw dynamic brake contactor in the main circuit, is shown in Fig. 43. To simplify this diagram, the diagram for the A.C. motor starter has not been incorporated.

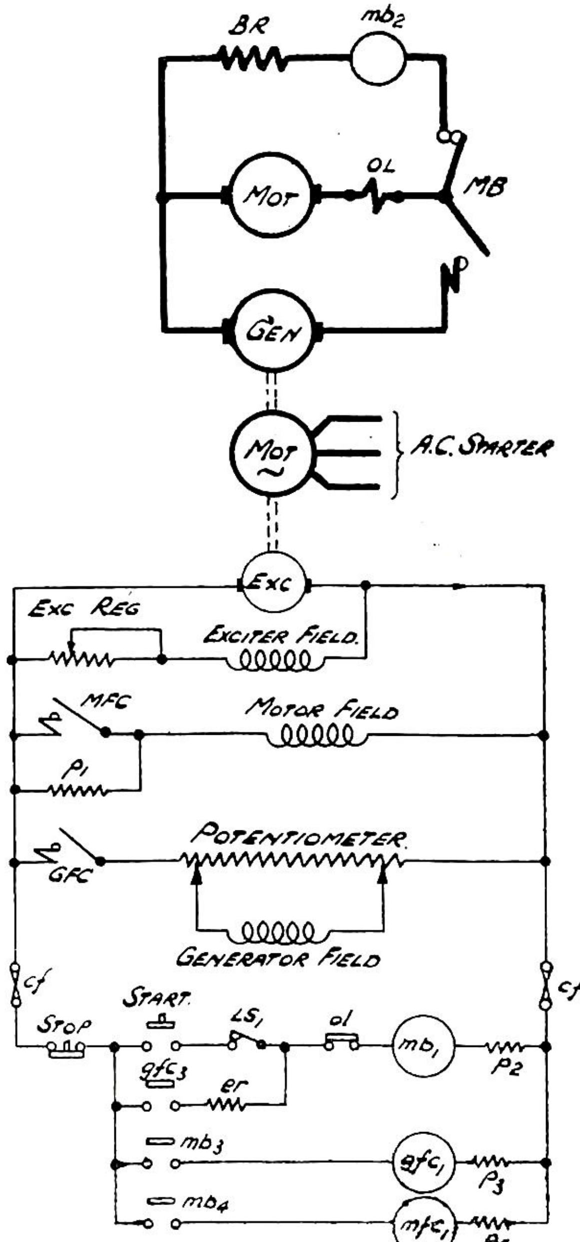
A small regulator resistance is included in the shunt field of the exciter to allow adjustment of the voltage. The generator and the motor field are energised by field contactors MFC and GFC respectively. The reversing generator field potentiometer is of the hand-operated type with one start interlock switch LS_1 to ensure starting with weak generator field (slow speed).

Depressing the start button energises the shunt coil mb_1 of the main-and-brake contactor MB through LS_1. MB closes and also closes the switches mb_3 and mb_4, which energise gfc_1 and mfc_1. Contactor MB is maintained by a switch on contactor GFC. Switch gfc_3 also inserts economy resistance *er* in the coil circuit of MB. Depression of the "Stop" button will cause MB to drop out and complete a dynamic brake circuit for the motor through hold-on coil mb_2 and brake resistance BR. A permanent resistance *p* is connected in parallel with contactor MFC to secure a definite motor field for braking. It also provides a path for the discharge of the motor field on opening of MFC. Note that none of the field circuits must be fused.

If push-button control of the motor speed is required, a pilot-motor has to be incorporated, driving the potentiometer regulator. The scheme for such a drive is shown in Fig. 13, and also Fig. 45 shows a diagram for a similar purpose.

Ward-Leonard sets for larger motors (100 H.P. and more) are usually arranged without any switches in the main circuit between generator and motor, since these would become too heavy. To provide quick reversing or stopping special schemes for the field control are required or specially-built exciters are used. This is necessary to overcome the magnetic inertia of the motor and generator fields.

Ward-Leonard control is also very suitable for the drive of reversing machinery, for example, machine tools such as planers, grinders, etc. The reversal of the generator field at the end of each stroke provides a gentle but firm braking of the motor and rapid acceleration in the opposite direction. This gentle braking is due



BR
mb2
MOT
OL
MB
GEN
MOT
A.C. STARTER
EXC
EXC REG
EXCITER FIELD.
MFC
MOTOR FIELD
P1
POTENTIOMETER
GFC
GENERATOR FIELD
cf
cf
START.
STOP
LS1
ol
mb1
P2
gfc3
er
mb3
gfc1
P3
mb4
mfc1
P4

Fig. 43.

to the magnetic inertia of the generator field. Reversing switches operated by the machine control the motion and, if required, special limit switches accelerate and retard the motor during the strokes. All these switches are operated by dogs, fixed to the table, etc., of the machine.

Fig. 44 shows a scheme of this kind. Different speeds are available for the two strokes (for example, working and return stroke). This is provided by one regulating resistance with two brushes, one for each stroke, and each connected to the corresponding field contactor, by means of which the reversal of the generator field is effected. Since the circuit of the generator field is continuously interrupted, a discharge resistance DR is fitted in parallel. A limit switch in series with the stop button acts as a safety switch and on dropping out, MB provides dynamic braking for the motor. The motor field is constantly energised and not variable, all the speed control being obtained by varying the generator field. Switch mb_3 maintains mb_1 and also inserts economy resistance *er*. Switch mb_4 provides the circuit for the forward or reverse field contactor FC and BC, the reversing switch energising the one required. Both are mechanically and electrically interlocked.

(2) Booster Control.

This is generally used only where a D.C. supply is available, although there are also A.C. booster schemes in use for some special purposes (paper mills, etc.). Booster control provides stable slow-speed conditions for the motor and the M.G. sets are smaller than the Ward-Leonard sets. Regenerative braking is possible, but not usually incorporated without special protective features, such as reverse current relays, excess speed relays, etc., since a closed circuit : main motor armature-booster generator armature-M.G. motor armature exists and with all the controls supplied from the same circuit, a circulation of energy is possible which might lead to the destruction of the booster set should the main supply fail during the braking period. If braking is required, dynamic braking is preferred.

Fig. 45 shows a comprehensive scheme with auto-solenoid starter for the M.G.-set motor and with pilot-motor-driven potentiometer regulator for the booster generator field. Inching, retarding and accelerating features are also incorporated. The pilot-motor is provided with dynamic braking to ensure quick stopping after release of the speed-control push-buttons.

Before the main motor can be started the booster motor must be running. To ensure this, contactors 1C and 2C have to be closed and the solenoid starter then accelerates the motor. At the end of this process, switch as_4 will close and only now can the main motor circuit be completed.

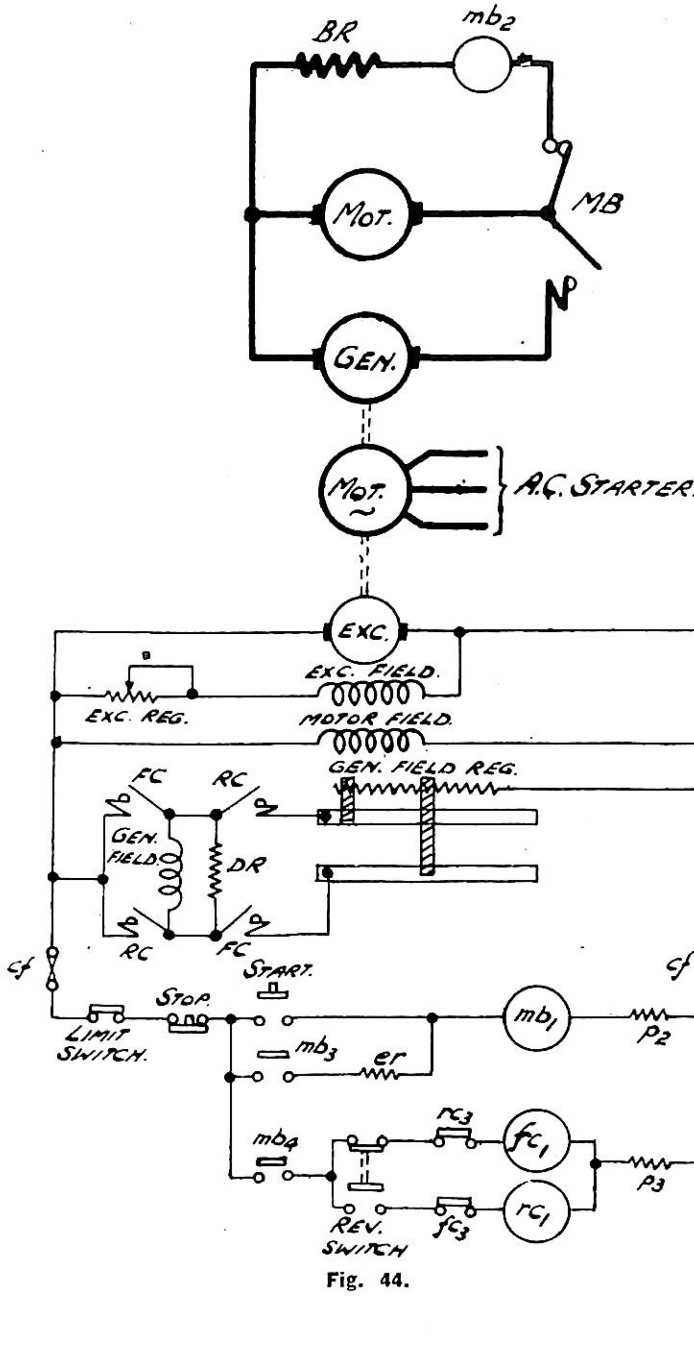
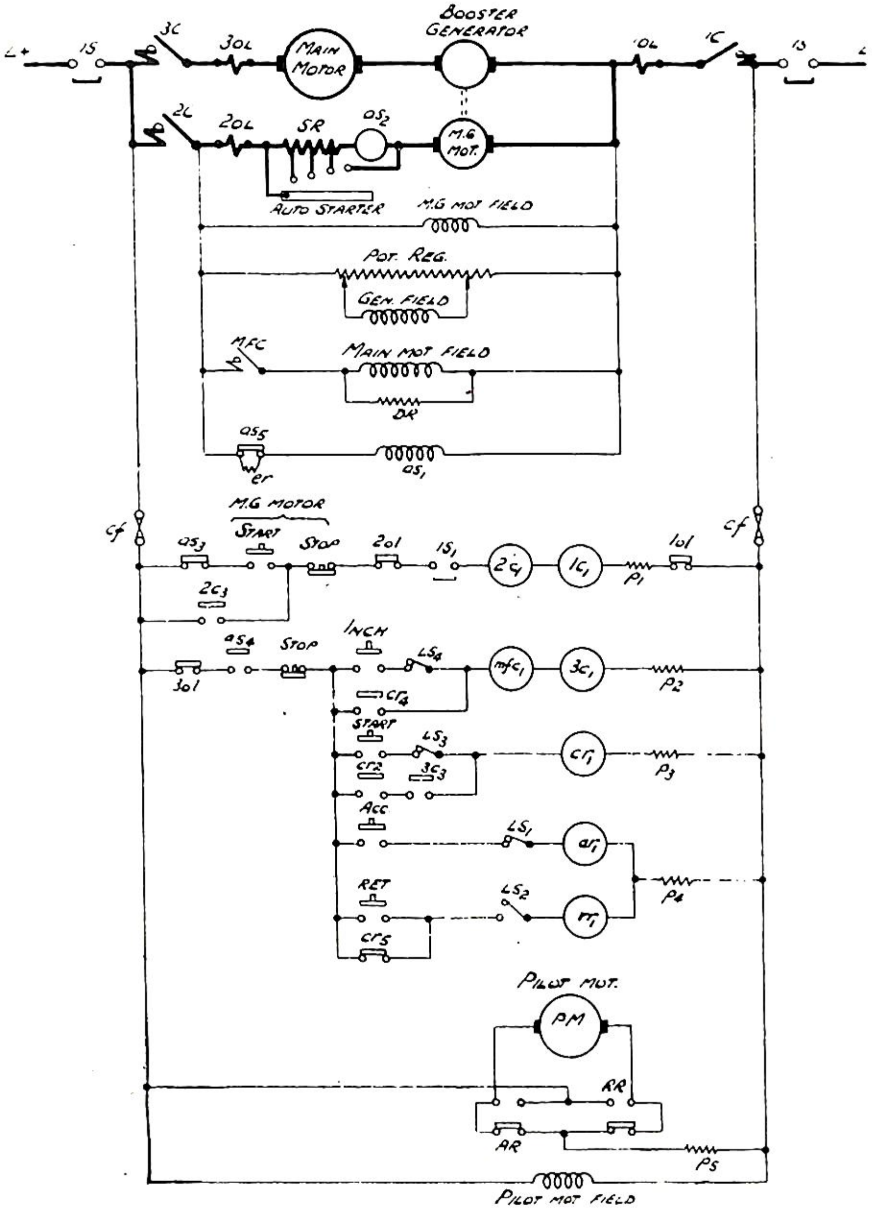

BR
mb2
MB
MOT.
GEN.
MOT.
A.C. STARTER.
EXC.
EXC. FIELD.
EXC. REG.
MOTOR FIELD.
GEN. FIELD REG.
FC
RC
GEN. FIELD.
DR
RC
FC
cf
cf
START.
STOP.
LIMIT SWITCH.
mb1
P2
mb3
er
mb4
rc3
fc1
P3
rc1
fc3
REV. SWITCH

Fig. 44.



BOOSTER GENERATOR
MAIN MOTOR
M.G MOT.
AUTO STARTER
M.G MOT FIELD
POT. REG.
GEN. FIELD
MAIN MOT FIELD
M.G MOTOR
START
STOP
INCH
ACC
RET
PILOT MOT.
PM
PILOT MOT FIELD

Fig. 45.

Depressing the "Start" button closes control relay CR, cr_1 being energised through start interlock switch LS_3 on the potentiometer regulator. Coil cr_1 is maintained by switches cr_2 and $3c_3$. Switch cr_4 is also closed and energises mfc_1 and $3c_1$. The main motor can now start and will run in bottom speed. In order to speed it up, the "Accelerate" button has to be depressed, energising the accelerating relay AR through top-speed limit switch LS_1. AR changes over and energises the pilot-motor armature for forward running. As soon as the button is released, AR drops out and short-circuits the pilot-motor armature through RR, thus providing dynamic braking.

By depressing the "Retard" button, the retard relay RR is energised and reverses the connection to the pilot-motor armature. Resetting of the potentiometer regulator is controlled by switch cr_5, which energises rr_1 through the bottom speed-limit switch LS_2.

To inch, the "Inch" button has to be depressed energising mfc_1 and $3c_1$. However, these contactors do not maintain and drop out again after the button is released. Limit switch LS_4 is included in the inching circuit. This switch is only closed in the "slow-speed" position of the potentiometer regulator, and should the accelerate button be depressed at the same time and the regulator start to move, LS_4 would break and trip the starter. Inching is thus only possible at slow speed.

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